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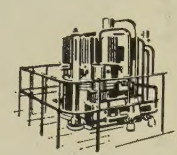

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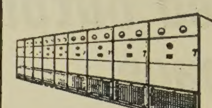

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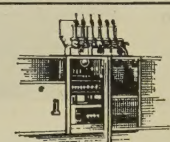

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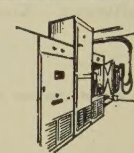

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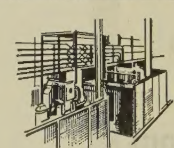

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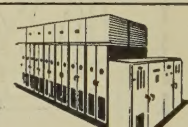

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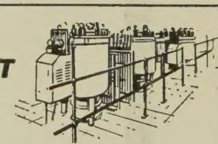

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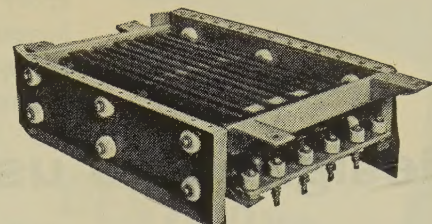

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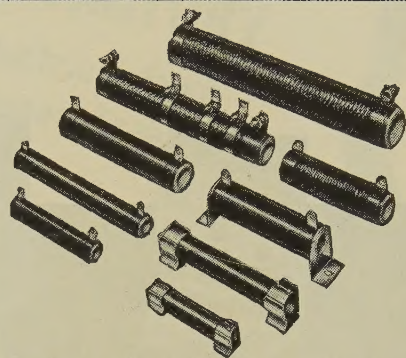

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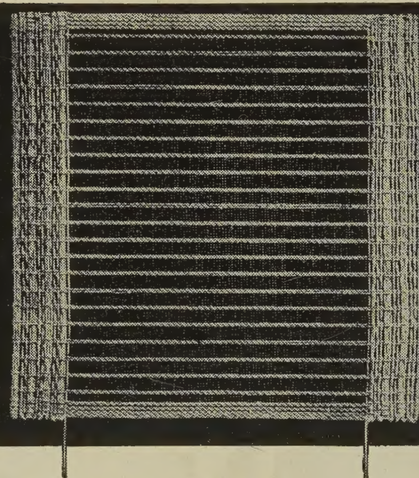

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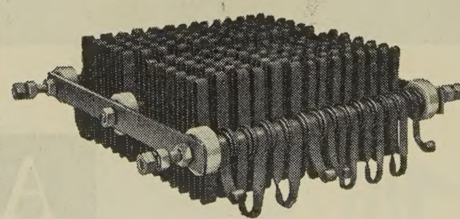

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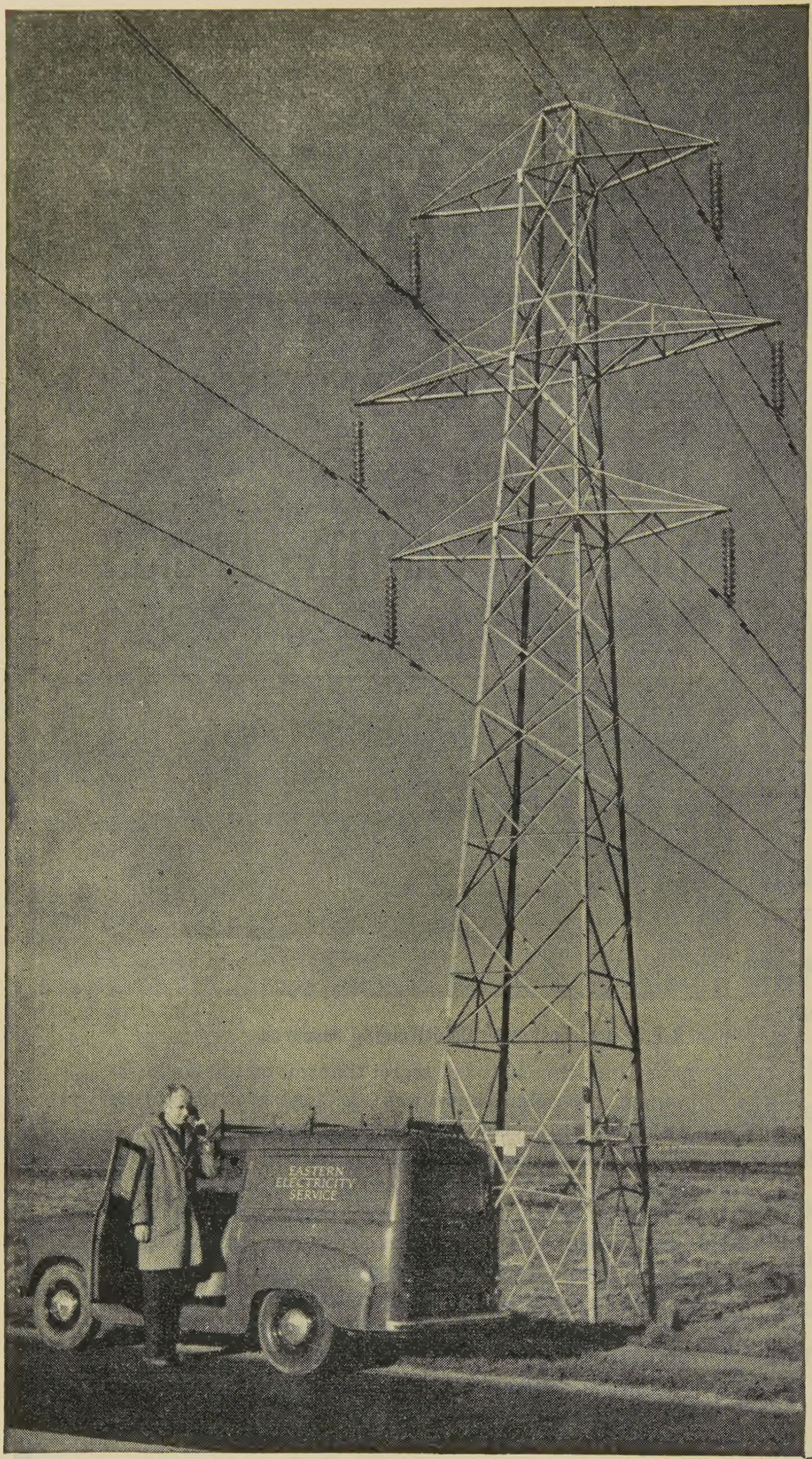

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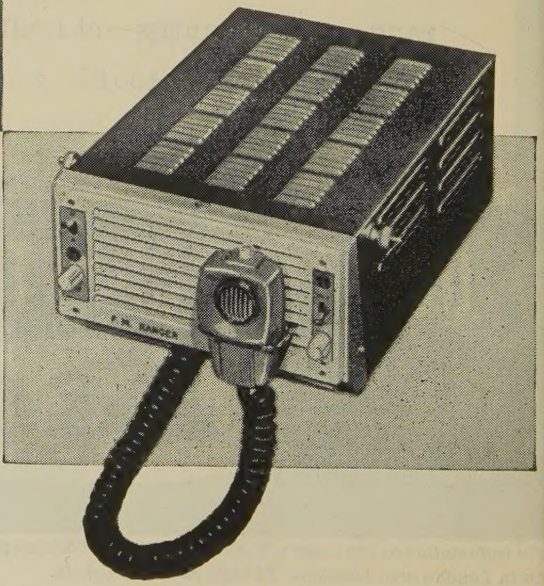

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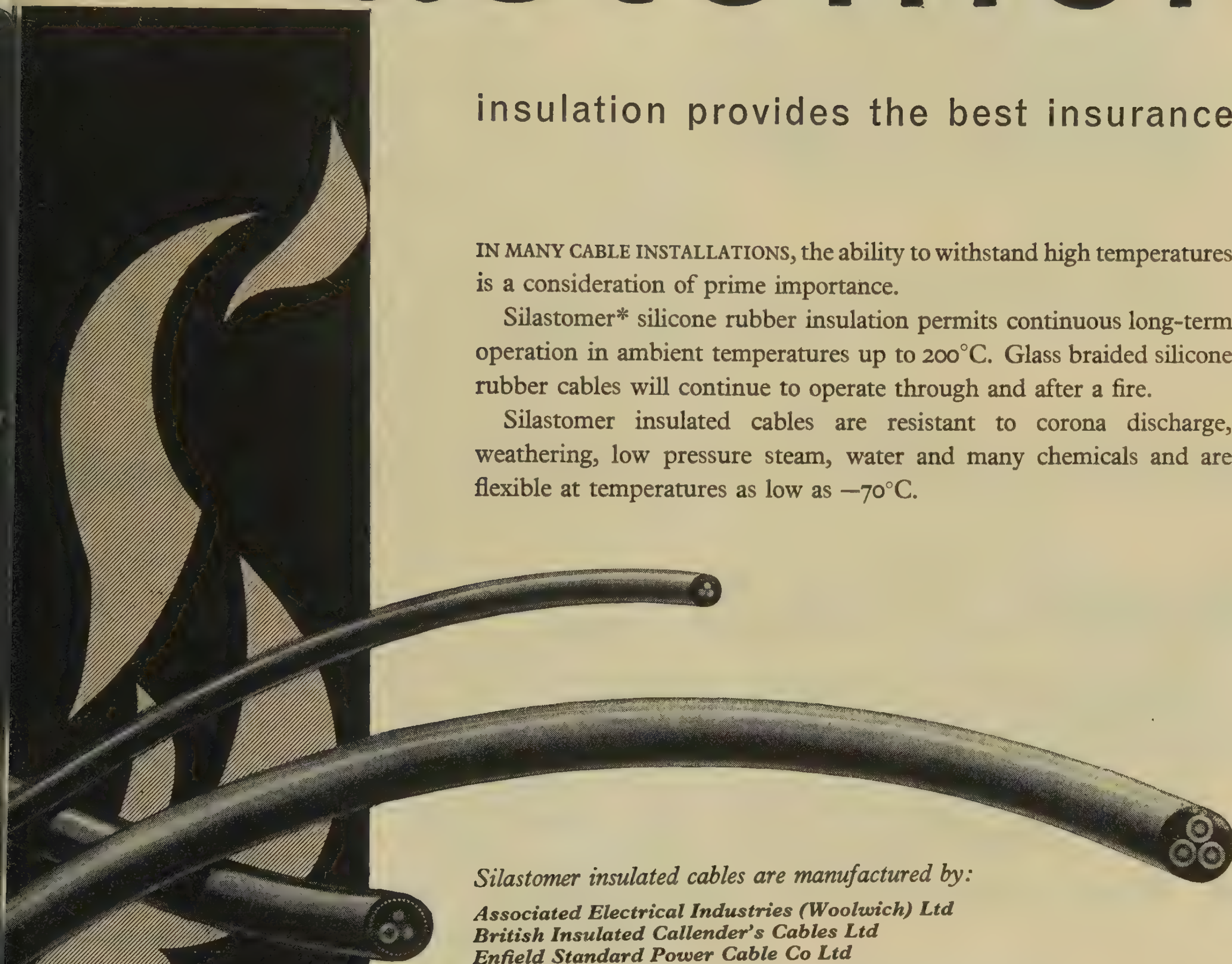

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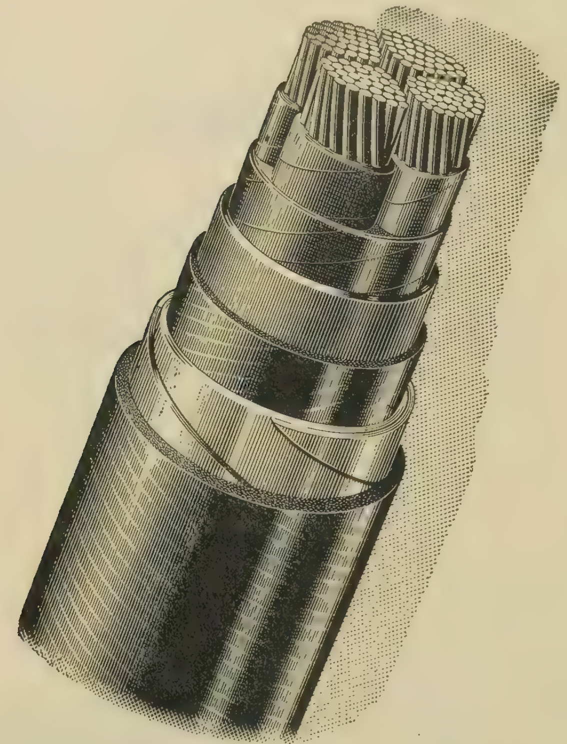

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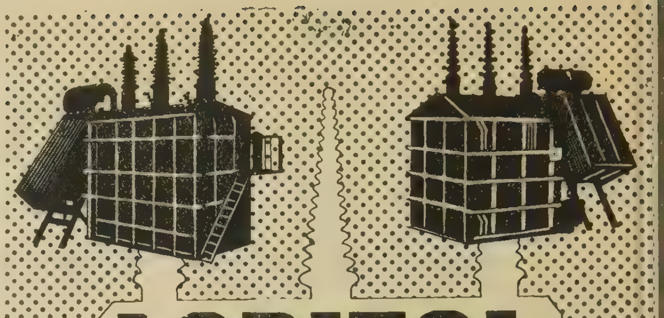

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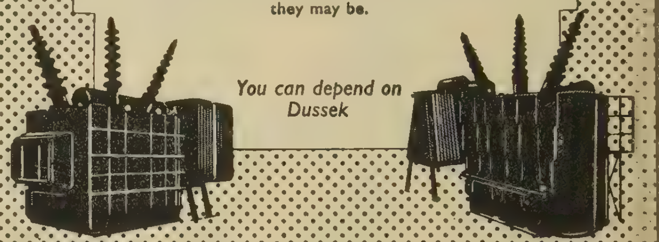

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CENTRE AND SUB-CENTRE CHAIRMEN'S ADDRESSES

The Institution of Electrical Engineers
Abstract No. 3228
Apr. 1960
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NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By F. J. HUTCHINSON, M.Eng., M.I.Mech.E., Member.

'PAST, PRESENT AND FUTURE'

(ABSTRACT *of Address delivered at* MANCHESTER, *6th October*, 1959.)

The first part of the address deals with the past and provides two specific glimpses into the future in respect of data logging and of the generation of electrical energy by means of fuel cells without the use of turbo-generators.

The next step is to study the trends of technical progress and cost which are indicated in Fig. 1. Curve (*a*) shows the tremendous strides that have been made during the last ten years in

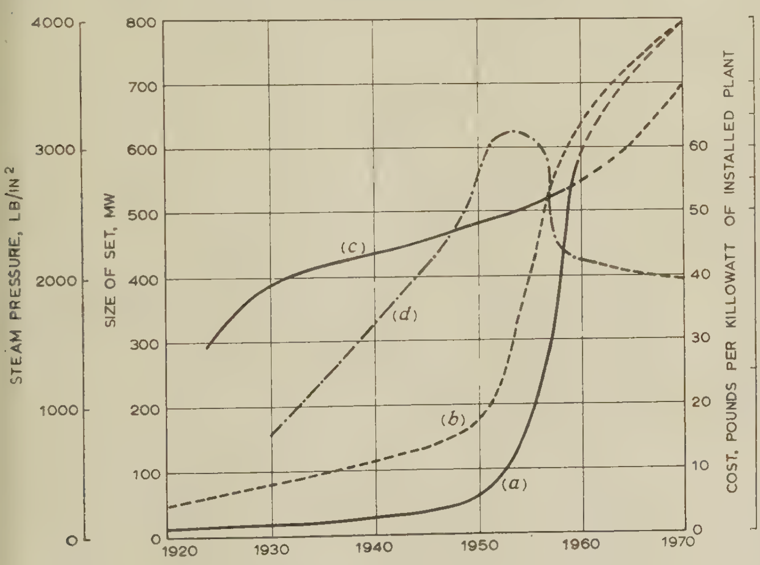


Fig. 1.—Thirty-year variations.
(*a*) Size of set.
(*b*) Steam pressure.
(*c*) Steam temperature.
(*d*) Cost per kilowatt.

the capacity of the turbo-alternator-boiler units, culminating with the 550 MW sets the rating of which has been accepted as a world standard, in so far as American electricity undertakings have ordered sets of this size not only from Britain but also from the Continent. Alongside this trend there has followed a considerable increase in steam pressures and a more modest increase in steam temperatures [curves (*b*) and (*c*)]. The impact of further increases in pressure and temperature will be considered later.

An examination of curve (*d*) showing cost per kilowatt of installed generating capacity is a very rewarding exercise. The purchasing value of money depreciated by approximately 66% from the early 'thirties to the early 'fifties, and curve (*d*) shows that the cost per kilowatt followed that trend. In 1948 the British Electricity Authority—now the Central Electricity Generating Board—was formed, and very soon (about 1953) the upward trend was halted. In 1957 a 120 MW station at Rogerstone was built for £59 per kilowatt; the 760 MW station at Kincardine is estimated to cost £47 per kilowatt. It is understood that the 1 000 MW station at High Marnham will cost £45 per kilowatt, and that the 1 100 MW station at Thorpe Marsh will be built for approximately £42 per kilowatt.

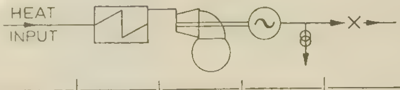
From the foregoing the influence of 'size effect' can be noted, and it is probable that such large blocks of power would never have been contemplated had the country still been split up into a large number of municipal undertakings and power companies. The Central Electricity Generating Board deserves acclaim for the imaginative manner in which it has approached this problem. For our third look into the future it is suggested that 800 MW sets will shortly not be uncommon, and that designs for supercritical pressures of 5 000 lb/in² associated with temperatures of 1 200–1 500° F will be available within the next ten years.

The reasons for such a statement require examination and clarification, and this can best be done by reference to Table 1. It will be seen that the pampered and cosseted turbine is the villain of the piece. In accordance with well-known thermodynamic principles, a greater proportion of useful work can be obtained by expanding steam through a turbine to a common vacuum when the initial steam pressures and temperatures are

Mr. Hutchinson is with Kennedy and Donkin.

Table 1

ALLOCATION OF LOSSES PER ANNUM FOR VARIOUS STEAM CONDITIONS

Pressure	Temperature					
lb/in²	deg F	%	%	%	%	%
600	850	100	14	56·25	1·75	28
900	900	100	13	55·00	2·00	30
1 350	950	100	12·5	53·75	2·25	31·5
1 500	1000/1 000	100	11	52·50	2·50	34
2 350	1050/1 000	100	10	49·00	3·0	38
3 500	1100/1050/1 000	100	9	48·25	3·75	39
4 500	1200/1050/1050	100	9	46·50	4·00	40·5

high than when they are low, and it can be seen that the percentage rejection of heat by the turbine through the condenser to the circulating water decreases progressively as the initial thermal conditions are increased and the reheat feature is incorporated in the design. The boiler efficiency remains substantially constant as this is largely determined by the outlet temperature of the flue gases.

A 1 200 MW station with an annual thermal efficiency of 31·5% and annual load factor of 70% would consume approximately $3 \cdot 4 \times 10^6$ tons of coal per annum. When running with an efficiency of 40·5% approximately $2 \cdot 6 \times 10^6$ tons of coal will be used. The saving—$0 \cdot 8 \times 10^6$ tons at £4 per ton—is quite appreciable.

Now for a final and somewhat more comprehensive look into the future, for which Table 2 will form the basis of our considerations.

Table 2

ANTICIPATED STATION ANNUAL HEAT RATES FOR ADVANCED THERMAL CYCLES

(Referred to 2 350 lb/in² and 1 050° F)

Pressure	Temperature	Decrease in heat rate	Station annual heat rate	
lb/in²	deg F	%	B.Th.U./kWh	
2 350	1 050–1 000	datum	9 020*	
3 500	1 050–1 000	2·0	8 840	Pressure only increased
4 500	1 050–1 000	2·5	8 795	
3 500	1 100–1 050	2·8	8 767	Pressure and temperature increased
3 500	1 200–1 050	3·6	8 695	
4 500	1 100–1 050/1 050	5·25	8 546	
4 500	1 200–1 050/1 050	6·75	8 411	

* Published figure for Kyger Creek generating station.

In Britain the Portobello generating station was operated from 1953 to 1957 at an annual heat rate of approximately 10 800 B.Th.U./kWh. In 1958 this was improved upon by the Portishead station with a heat rate of 10 610 B.Th.U./kWh. In America the last published figures I have seen relate to the Kyger Creek station with a national minimum annual heat rate of approximately 9 020 B.Th.U./kWh. This station is designed for a nominal steam rejection pressure of 1·4 in Hg, and it is thought that similar stations in Britain designed for a 29 in Hg vacuum will show slightly decreased heat rates. On this basis, therefore, the subsequent annual heat-rate figures shown in the Table may be regarded as conservative.

The upper portion of the Table shows that a gain of 2·5% can be obtained by increasing the subcritical steam pressure of 2 350 lb/in² to the supercritical pressure of 4 500 lb/in² without any increase in temperature.

When considering a 1 200 MW station running at a load factor of 70%, the annual coal bill for which will be of the order of £11 million, it is clear that a 2·5% saving will amount to approximately £275 000 per annum. This can be obtained by increasing steam pressures, leaving the temperatures at the basic values, and is well worth examination. Capitalized at 7%, this saving amounts to nearly £4 million, or £3·3 per kilowatt.

Increases in the steam temperatures as the pressures increase offer a still greater reward, as can be seen from the lower portion of Table 2. A decrease of 6·75% on the basic coal bill of approximately £11 million results in an annual saving of £750 000, which when capitalized amounts to £9 per kilowatt.

It will have been noticed that my remarks relating to the amount of coal consumed and the savings to be gained by decreased annual heat rates have always been referred to a 1 200 MW station. An examination of the supercritical pressure range on an economic basis shows that the minimum size of unit for these conditions is approximately 250 MW. This is due, to some extent, to the influence of the 'size effect' previously mentioned. For this reason a lower limit of 300 MW for the boiler-turbine unit has been chosen for examination, and a station equipped with four such units has been taken arbitrarily as having the ultimate desirable capacity.

The realization of supercritical steam pressures and extra-high temperatures is more difficult to achieve than has yet been made clear. It is thought that increased pressures alone can be met by using the basic ferritic steels which are being built into the various plant components at the present time. Metallurgists in Britain, America and on the Continent are continually striving to produce long-life steels which will work reliably and continuously at temperatures of 1 200–1 500° F when designed for stresses commensurate with the designers' requirements and at a cost which is economical. Considerable success has already attended these researches.

In America, at Philo, a 125 MW unit has completed a year's working under supercritical pressure and normal steam temperature conditions. The 'teething troubles' have been many and varied, but the information gained from the numerous shut-downs has proved the adaptability and versatility in operation of the supercritical thermal cycle. As a result a further 450 MW supercritical set is already under construction. The 150 MW units at Kearney and the 300 MW units at Burlington have been operated successfully for some years at conventional steam pressures and at temperatures of 1 100° F. Austenitic steel is used in the high-temperature zones of these units, and a great deal of experience regarding the workability of this material, particularly its weldability, is available.

In Germany there is a cross-compound arrangement with a gross output of 75 MW working with initial steam conditions of 4 500 lb/in² and 1 110° F. Also in Germany there are three back-pressure sets each with a steam throughput of 43 000 lb/h operating satisfactorily at 2 350 lb/in² but with an initial temperature of 1 200 F. These sets, one of which has been in operation for six years and one for fifteen months, have latterly given commercially trouble-free operation.

The steam supply from the boiler to the turbine is effected for three of the units by small-bore pipes of Austenitic material approximately 0·47 in thick. The main composition of the steel for the pipes is 16% chromium, 16% nickel and 1·8% molybdenum, and the pipes run at a cherry-red heat. The permissible stress under running conditions is 3·8 tons/in² but the design stress is only 2·6 tons/in². It is understood that research into steels for 1 300° F is already being undertaken.

From America and Germany, therefore, there is ample

evidence that technically the use of supercritical steam pressure is a practical proposition as is the use of steam at 1 200° F. During the next decade I believe it will be acknowledged that they can be used together.

In the establishment of a supercritical extra-high-temperature steam cycle the main steam pipes are considered by designers in the users' organizations, and by manufacturers, to be the most difficult portion of the plant for which to obtain an economical solution. They must be constructed throughout of special heat-resisting steel which a few years ago was confined to the Austenitic range, and the price in those days made this material economically unusable. On the Continent the price of Austenitic steel to-day is approximately 60% of what it was four years ago. Recent researches have produced a 13% chrome-steel which has very suitable characteristics in the temperature range required, and this coupled with the increasing use of Austenitic material may have the effect of lowering its price still further. The amount of Austenitic material required for the higher-temperature zones of the boiler and superheater and for the turbine is not considered to be economically unjustifiable.

As steam pressures are increased to the region of the supercritical, the natural-circulation boiler which is in general use in this country begins to require the help of forced circulation. From the point where the supercritical pressure is reached, if not before, the fully-forced-circulation boiler must be used. This is popularly known as the 'once-through' boiler.

Fig. 2 is a diagrammatic arrangement of such a boiler. Two

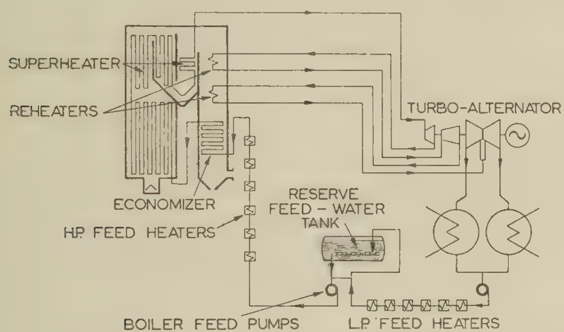


Fig. 2.—Basic diagram of main plant.
Supercritical pressure and high temperature.

stages of reheat have been included, and the high-pressure feed-water heaters are shown alongside the boiler, not adjacent to the turbine, and on the discharge side of the main boiler feed pumps. The reverse feed-water tank, which is of a pressurized type, can provide at least half an hour's supply to the boilers. The quality of the feed water must be in accordance with the most stringent specification.

The boiler furnaces of the future could with advantage be of the slag type or of the continuous slag-rejection type, where the ash-fusion characteristics of the coal are suitable, in order to avoid the difficulty and cost of collecting and disposing of, as flue dust, 85% of the ash in the coal burned. They should also be pressurized without the installation of induced-draught fans.

It is well known that extra-high-pressure pumps are generally of the barrel type without an external joint on the horizontal diameter. The outer casing of the supercritical-pressure turbine could assume the same appearance with an unbroken circular cross-section. The stationary blade carriers would be split across a horizontal diameter, and the spindle located as usual between the top and bottom halves, which are registered and held together by dowel pins and light bolts. The whole of this assembly is then inserted into the cylinder of the outer casing and secured therein by a clamping collar which is fixed in position by rotation in a manner similar to the securing of a breech in a large gun. In operation, full-pressure steam is admitted to spaces arranged between the inside of the outer casing and the outside of the stationary blade carriers, thus ensuring that no appreciable differential bursting pressure will exist to separate the two halves of the stationary blade carriers. Fig. 3 shows a longitudinal section of such a turbine with the

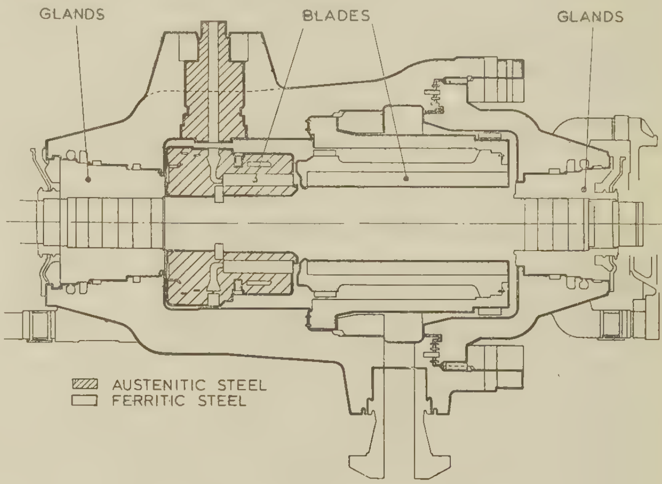


Fig. 3.—Supercritical-pressure turbine.

inserted portion delineated by a thick black line. The comparatively small amount of Austenitic steel required when using steam at extra-high temperatures has already been noted. The extent of this is shown cross-hatched.

Owing to the high pressure to which feed-water heaters will be subjected in a supercritical-steam-pressure plant it is desirable to keep their diameters small in comparison with those of present-day conventional heaters. This leads to a series of heaters in parallel. The boiler feed pumps, be they turbine or motor driven, will normally run at 5000–10 000 r.p.m. Owing to the large amount of pumping power required, probably of the order of 20 000 h.p. per unit, it will be desirable to provide a number of pumps in parallel if motor driven from the station auxiliary system. Speed variation can preferably be obtained by inserting a hydraulic coupling in the shaft system between the motor and the gear which is necessary to produce running speeds of over 3 000 r.p.m.

The control of a 1 200 MW four-set station with advanced thermal conditions should be effected from two control rooms each equipped with the instrumentation required for two units. Five operatives in each control room would be adequate for the starting-up and the shutting-down of the units and for the adjustments necessary due to load variations. The total personnel would be of the order of one man for each 2½ MW of installed generating plant.

The aim of the electricity supply industry is to sell electrical energy to users at the lowest economic price. The average total cost of generation in the middle 'thirties was approximately 0·49d./kWh when coal was purchasable at under 20s. per ton and with the price levels ruling at the time. To-day, with general price levels multiplied by three and coal costing about 80s. per ton, the average cost of generation is approximately 0·9d./kWh. This is indeed a tribute to the electricity supply industry. It is suggested, however, that in Britain a supercritical-pressure high-temperature 1 200 MW station would generate electrical energy at a cost of under 0·5d./kWh.

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SOUTH-WEST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. E. SAYERS, B.Sc., Member.

'ELECTRO-PRECIPITATORS: SOME DESIGN AND OPERATING PROBLEMS'

(ABSTRACT *of Address delivered at* GLASGOW, 21*st October*, 1959.)

Although many papers have been published on electro-precipitators, few have dealt with performance and development tests in the field. This Address reviews the results of an extended period of development testing of a novel large-scale experimental precipitator installation which has been fully described elsewhere.*

Attention is directed especially to those features of general interest and application to conventional precipitator installations.

Unusual Features of the Experimental Installation

The main features of this installation were

(*a*) The precipitator was located between the outlet from a pulverized-fuel-fired power-station boiler and its associated air-preheater, resulting in a high treated-gas temperature.

(*b*) A high gas-treatment velocity was adopted.

(*c*) The collecting surface (small hexagonal tubes) was sectionalized in compartments (sectors) and arranged for cleaning by periodic application of a high-velocity cleaning-gas stream, whilst temporarily isolated from the main gas flow.

(*d*) Final extraction of dust from the system was by a mechanical collector in the (small volume) cleaning-gas circuit.

The nominal duty of the plant, which commenced operation in April, 1954, was to clean 120 000 ft^3/m of flue gas at 600° F with a gas-treatment velocity of 40 ft/s.

This plant was later augmented by two small pilot precipitators with modified electrode and cleaning systems.

Performance Fluctuations

Whilst initial operating results with the new plant were generally good, it soon became apparent that unacceptable performance fluctuations were being experienced with variations in boiler load and combustion conditions and also, later, with variations in fuel supplies which came from several sources (the United Kingdom, the Continent and the U.S.A.). A comparison of the leading physical and chemical properties of these coals revealed no explanation for the variations in precipitator performance. Further reference is made to this matter later.

Power Supply Units

To meet operational requirements the electrodes in each sector of the precipitator were provided with an independent high-voltage power supply, comprising a 3-phase transformer and a bridge-connected selenium rectifier. To permit voltage variation over the range 5–20 kV, and for flashover suppression, series- and parallel-connected saturable reactors were provided in the primary lines to each transformer with provision for varying the (d.c.) saturating currents in the control windings of these reactors.

Automatic flashover suppression was triggered by a thyratron, normally blocked by a component of the negative precipitator operating voltage and arranged to fire on collapse of this voltage due to a flashover.

Switching of the reactor saturating currents was originally effected by relays, but a magnetic-amplifier control circuit was later substituted and a time delay provided to prevent operation on self-clearing flashovers. The result was selective, effective and fast flashover suppression, and under these conditions the operation of the precipitator was better than on the more peaky waveform from a single-phase rectified source.

Electrodes

The main precipitator originally contained two sets of collecting tube nests, in series, with a two-element (ionizing and collecting) electrode in each hexagonal cell.

Various configurations of high-voltage electrodes, as described, were tested in the pilot precipitators with the object of ameliorating the effects of 'back ionization' and eliminating the performance fluctuations experienced with different coals. The electrode system finally selected comprised two independent ionizing stages in series in a single tube-nest.

For adverse conditions a two-element discharge electrode was developed comprising an ionizer surrounded by a perforated shield and so arranged that the voltage applied to, or induced on, the shield could be controlled independently of the ionizing voltage. Adjustment of the shield voltage permits adjustment of the ionization characteristic of the electrode system, and tests and experience with this type of ionizer have been successful under extremely adverse operating conditions.

Dust and Gas Characteristics

This section of the Address commenced with a more detailed review of the nature of the precipitator performance fluctuations experienced with the dust from 'difficult' coals, and referred to the results of tests made under conditions of varying boiler load, and also with steam injected into the flue gas ahead of the pilot precipitator.

Reference was then made to the effects of resistivity of the flue dust and to the results of tests showing the effects of coatings of dust on the precipitator electrode system and the necessity to relate the electrode cleaning effort to operating conditions.

In an endeavour to pin-point the particular dust or gas characteristics responsible for adverse operation, one of the pilot precipitators was operated as nearly as possible under constant conditions for several weeks, the main variables being fuel supplies and boiler combustion conditions.

During this period the precipitator performance was checked a number of times each day and frequent checks were made of the operating voltage, of the chemical analyses of the fuel and fly ash, of the water-vapour and carbon-dioxide contents of the flue gases, and of the resistivity of the dust and the conductivity of the flue gas.

The information recorded during these tests was presented graphically and the results of this investigation indicated that

(*a*) The only clear interdependence revealed by comparison of all the variable characteristics considered was that between precipitator performance and electrode voltage (for the constant corona discharge current used) during the tests.

(*b*) The variations in precipitator performance experienced with the different coals burned during the tests could not be attributed to differences in the resistivity of the associated dusts.

(*c*) Variations in the discharge characteristics of the carrying

* KLEMPERER, H., and SAYERS, J. E.: 'Design Aspects of an Electrostatic Precipitator for the Collection of Small Solids ahead of the Air Heater', *Transactions of the American Society of Mechanical Engineers*, 1956, 78, p. 317.

Mr. Sayers is with James Howden and Co., Ltd

gas appear to be the principal factor affecting precipitator performance.

The field work reviewed occupied some four years and demonstrated the practicability of efficient precipitation of fine flue dust from gases at temperatures up to 700° F with treatment velocities in the range 30–45 ft/s.

The tests demonstrated the dependence of precipitator performance both upon the fuel in use and upon combustion conditions and pointed the necessity for pilot-plant tests to establish basic design parameters for each new precipitator application considered. The possibilities arising from pre-treatment of the flue gases were also noted.

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SOUTH-WESTERN SUB-CENTRE: CHAIRMAN'S ADDRESS

By A. G. R. BELL, Associate Member.

'THE IMPACT OF NUCLEAR POWER STATIONS ON THE GENERATING SYSTEM'

(ABSTRACT *of Address delivered at* PLYMOUTH, *15th October*, 1959.)

From the wide variety of electrical topics available for my address, I have decided to give my personal views of the effect of introducing nuclear power generation on the interconnected supply system.

As a consequence of rapid advance in design, a modified nuclear programme was published in 1957 which aimed at commissioning 5 000 to 6 000 MW of nuclear generating plant by 1965, thus trebling the programme announced in 1955. This has since been revised, owing to restrictions on capital investment, for completion by 1966.

The major requirements of a nuclear site are a large expanse of water for cooling purposes and a substratum capable of supporting heavy loads. The site should be flat and at water-level, and there should be ample space for civil engineering works, etc. Other requirements are good road access, adequate supplies of fresh water for boiler make-up, and suitable routes for overhead lines to load centres. A further requirement imposed by the Government is that the site should be well away from built-up areas. Other interested bodies also have to be consulted, and preliminary investigation of a site may take up to two years.

Power station reactors of present design all depend on the fission process, in which a chain reaction is produced in uranium 235. The reactivity of uranium 235 depends on temperature and has a negative temperature coefficient which is used as the basic control of output of the reactor. This is an inherent safety property, because if the control system fails and the reactor increases in temperature it will eventually shut itself down. In the nuclear station this negative-temperature-coefficient control of a reactor is utilized in bringing the reactor up to power by removing control rods from the core with a minimum of coolant flowing through it, and when the required temperature is achieved heat is extracted by means of the cooling gas. To pick up load the flow of gas is increased, thus cooling the reactor and causing immediate increased reactivity and heat release which restores the temperature to the original figure.

Main reactor load control is by means of variable-speed fans circulating the cooling gas. At Hinkley Point a variable-frequency source with synchronous motors is used. This gives very close control of reactor output, but presents some serious problems. These include metering of the output and voltage control of the variable-frequency generators. Normal-type protection relays relying on induction cannot be used on a variable frequency, and the normal type of switchgear is designed for the frequency at which it is to operate. Another problem is that, if an additional motor has to be started whilst the remainder are on full load, it is necessary to run up a variable-frequency turbo-alternator specially to bring in an additional blower. Added complications arise because the reactor must never be left without a supply of cooling gas, and if there is a failure of the variable-frequency supply there must be alternative means of driving the fans to deliver 5% of their normal output. The fans themselves must be gas sealed on their shafts, and the carbon-dioxide coolant will be at a pressure of 150 lb/in^2. Being in direct contact with the core of the reactor, the carbon dioxide will be radioactive, and any oil used on seals must be able to withstand radiation. It must also be in a closed circuit and any carbon dioxide absorbed must be extracted before further use. Solutions have now been found to these problems.

As the conventional steam stations have to carry the load variations, the impact on them of the nuclear power programme is giving cause for serious consideration. In the planning of new stations full advantage is being taken of technological advances in design, and it has been found that, by utilizing large units of up to 550 MW capacity at extreme steaming conditions of pressure and temperature, we can operate at the highest possible efficiency and reduce both capital costs and running costs. We are facing the prospect of operating these sets under 2-shift conditions, which brings its own problems. The thermal cycling that the steam side of a plant has to sustain imposes great strain on the metals and great responsibility on the plant operators. The need for instrumentation is greatly increased, and the use of electronic equipment has been developed to measure any deflections or distortions taking place within the cylinders whilst sets are being run up. Very close control must be maintained of differential temperatures existing between the steam and the heavy metal masses of the turbine.

Off-load losses have received careful investigation and new techniques of operation have been developed. Thermal insulation has been improved to reduce these losses to a minimum. Turbines, boilers and associated controls have been designed to be efficient at partial loads as well as at full load, involving the development of variable-speed auxiliaries and variable-duty fuel-firing equipment.

By 1965 the nuclear generation capacity will be equal to the night-load available for the whole country. This will present the great problem of how to spread the load over the 24-hour period, and offers a challenge to Area Boards to develop night-load thermal-storage heating and other off-peak consumption. The Generating Board will need to investigate and develop pumped-storage hydro-electric schemes wherever possible.

There is a possibility of developing 3 000 MW of pumped

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storage in the south-west of England, and this could take a number of forms. Water at high level could be impounded within a suitable dam, with a second reservoir of smaller capacity at a much lower level. Several suitable sites are available in Devon capable of developing to 300–400 MW capacity, utilizing heads of up to 700 ft. The natural run-off is not important, as water can be used again and again without appreciable loss. This development could be made in conjunction with domestic and industrial supplies. Another form of pumped storage would be to utilize the steep-sided valleys near the coast. A second or lower reservoir would not be required, as the sea could be utilized. A danger would be possible contamination of agricultural land by sea water from the flooded valleys through faults in the rock formation.

Pumped storage is highly desirable in that, during off-peak periods, the pumps can be loaded to the full capacity of the station, and if the external system load increases, pumping can be reduced accordingly, keeping the overall load on the system constant up to the point where pumping ceases and generation commences. Then the full load can be picked up, thereby keeping the total load, as a whole, constant, with an external variation of double the capacity of the station, which means that the effective capacity of a pumped-storage station is twice its installed capacity.

Another source of night-load investigated is main-line railway electrification, but a complete survey has shown that one 400 MW generating station could satisfactorily supply the whole of the needs of British Railways if fully electrified throughout the country. This would not materially affect the overall position, being less than 10% of the country's existing night-load.

The electricity supply industry has operated on a shift basis for many years, and it is difficult to appreciate why industry as a whole cannot be converted to 24-hour working, thereby obtaining the greatest possible productivity and output from the capital invested in the machinery. This would solve all the problems of load factors.

PAPER AND MONOGRAPHS PUBLISHED INDIVIDUALLY

Summaries are given below of a paper and three monographs which have been published individually. The paper is free of charge; the price of the monographs is 2s. each (post free). Applications, quoting the serial numbers as well as the authors' names, and accompanied by a remittance where appropriate, should be addressed to the Secretary. For convenience, books of five vouchers, price 10s., can be supplied.

A New Form of Crane-Hoist Control using a 3 : 1 Pole-Changing Induction Motor. Paper No. 3226 U.

O. I. Butler, D.Sc., and V. Ahmad, Ph.D.

The basic practical requirements of crane-hoist drives are summarized and the latest developments, including closed-loop control methods, in satisfying such requirements with a.c. drives are discussed. In particular, the paper investigates the suitability of an economical design of a 3 : 1 pole-changing induction motor for crane-hoist drives.

In conjunction with a single-phase auto-transformer, the pole-changing motor enables the best use to be made of d.c. and a.c. dynamic braking, which further assists in reducing the energy dissipation in the motor circuits as well as reducing the number and size of the secondary-circuit resistors and contactors. It is shown that the performance characteristics are such as to satisfy crane-hoist requirements without undue complexity of the complete equipment.

The paper will be read at a London meeting during the 1960–61 Session.

Flux Distribution in a Permeable Sheet with a Hole near an Edge. Monograph No. 368 M.

B. V. Jayawant, Ph.D., B.Eng.

In the measurement of the distribution of magnetic flux in the cores of electrical machines by locating search coils in them, the presence of a search-coil will alter the flux in that region. It is therefore necessary to make a correction to the measured flux. The problem is the solution of Laplace's equation in two dimensions in a material assumed to be of constant permeability, and it has an analogy in hydrodynamics. The solution is obtained by a conformal transformation; it is found that the correction is quite significant when the distance of the centre of the hole from the edge is equal to its diameter.

Contact Losses due to Load and Parasitic Currents in Polyphase Commutator Motors. Monograph No. 375 U.

O. E. Mainer, M.Sc.Tech.

After brief reference to present methods of measurement, the interdependence of the brush losses due to load and parasitic currents is discussed and the need for measuring these losses simultaneously is argued. Owing to the impossibility of doing this satisfactorily on a motor, an apparatus for simulating brush parasitic currents is described and test data obtained with this apparatus are used to establish the argument. The effects of rotor power factor and speed on these losses are also discussed and established experimentally. Finally, a new test is described by means of which the total rotor I^2R losses of a polyphase commutator motor can be measured with reasonable accuracy. Curves obtained by this method of test using plain and sandwich brushes show the dependence of these losses on the coil e.m.f. between segments.

Calculation of the Current in Non-Linear Surge-Current-Generator Circuits. Monograph No. 376 S.

T. F. Monahan, B.Sc.

Surge-current generators are used to test non-linear resistors and surge diverters. Although the circuit is basically very simple, it is possible to calculate the surge current only by numerical solutions of the differential equation for particular values of the parameters. The paper gives the results of such calculations made at Manchester University on the differential analyser and the electronic computer. The application of the results to certain practical problems is discussed.

PROBLEMS OF ENGINEERING EDUCATION

CORRECTION

In the report of the group of German professors on p. 421 of the December 1959 issue of Part A of the *Proceedings* it was stated in error that the courses at the Battersea College of Advanced Technology are not honours-degree courses. In fact Battersea produces a high proportion of honours graduates, and it is regretted that the error was not noticed before publication.

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The Institution of Electrical Engineers
Paper No. 3145 U
Oct. 1959

THE APPLICATION OF IRRADIATION IN INDUSTRY

By M. C. CROWLEY-MILLING, M.A.

(*The paper was first received* 29*th December*, 1958, *and in revised form* 18*th August*, 1959. *It was published in October*, 1959, *and was read before the* NORTH-WESTERN CENTRE 3*rd November*, THE INSTITUTION 5*th November*, 1959, *and the* RUGBY SUB-CENTRE 9*th March*, 1960.)

SUMMARY

A survey of the types of radiation shows that only γ-rays and high-speed electrons are worth consideration for industrial radiation. Possible applications and the methods of producing such radiation are discussed briefly. The problems of the introduction of irradiation into industry are examined, and the methods applying electron irradiation are explained in detail. A typical installation is described, and the economic aspects are considered.

(1) INTRODUCTION

Over the last ten years, many workers have been investigating the effects of ionizing radiation on various materials, and it has been shown that irradiation can be a commercially useful process. Up to date, it has only been used in comparatively few instances, but it is anticipated that the number of installations will increase very greatly in the next ten years.

The aim of the paper is to provide a brief engineering approach to the special problems of applying irradiation in industry. It is not possible to deal with any one problem at great length, but it is hoped that the references given will enable any particular point to be pursued further.

(2) TYPES OF RADIATION

There are two types of ionizing radiation, namely electromagnetic waves and streams of particles. The electromagnetic waves of interest are those of very short wavelength, known as X-rays or γ-rays. It has been usual to call such radiation X-rays when produced by the slowing of high-speed particles in a target material, and γ-rays when produced by radioactive disintegration, but they are physically identical.

Ionization can be caused directly by charged particles, such as electrons, and indirectly by neutral particles, i.e. neutrons. High-energy charged particles heavier than electrons are expensive to produce and have a much smaller range than electrons of the same energy, and are not likely to be applied commercially. Irradiation by neutrons can cause the production of radioactive isotopes of some materials, and so is not to be recommended.

This leaves high-energy electrons as the only particles suitable for industrial irradiation. Streams of electrons are sometimes known as cathode rays, and, if produced by radioactive disintegration, they are also known as β-rays.

(2.1) Methods of Ionization

The mechanism of ionization differs between electrons and X- or γ-rays. Electrons with energies up to about 10 MeV give up almost all their energy by direct electron-electron interaction, a fixed amount of energy being given up at each interaction, so that there is a definite maximum range, depending on the initial energy of the electrons and the density of the material. Fig. 1 shows the variation of ionization with depth in water for electrons of various energies. For practical purposes it can be assumed that the depth of penetration for electrons of a given energy

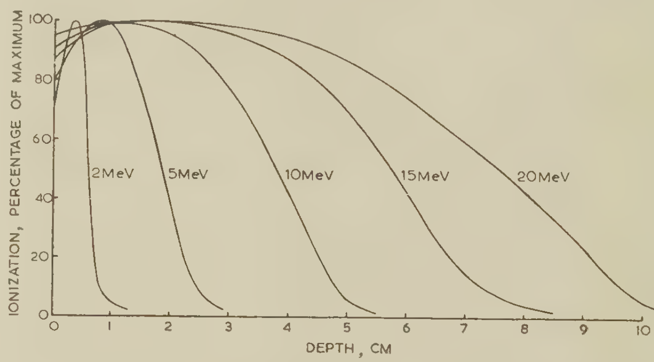

Fig. 1.—Variation of ionization with depth in water, for electrons of specified energy.
Data obtained from Reference 41.

will vary inversely as the density of the material. At initial energies over 10 MeV, electrons lose an appreciable proportion of their energy in the production of X-rays, and this proportion is higher for the high-density materials. Furthermore, these X-rays can cause the production of neutrons, resulting in radioactivity in certain materials.

The absorption of X-rays and γ-rays is explained in terms of three effects—Compton scattering and photo-electron and pair production.[1] Ionization is caused by the resulting secondary electrons, and the amount of ionization produced in a material falls approximately exponentially with depth. Fig. 2 shows this variation for the γ-rays from cobalt 60 and caesium 137, absorbed in water. A greater thickness of material can be treated with γ-rays than with electrons of the same energy, but there will be considerable variation of dose through a thick specimen.

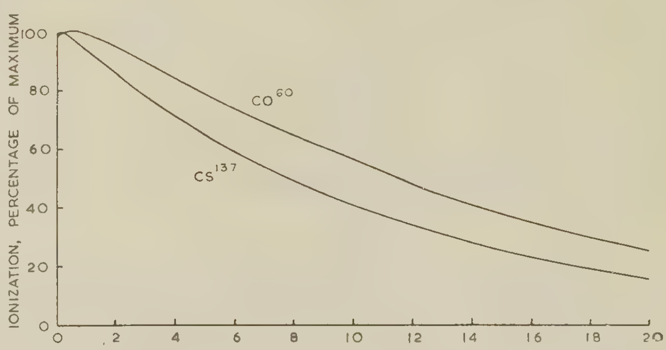

Fig. 2.—Variation of ionization with depth in water, for γ-rays from cobalt and caesium.
Data obtained from Reference 41.

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.
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(2.2) Dose Units and Activity

In nearly all cases, the ionization produced, and thus the desired effect, is proportional to the power absorbed in the material. Several units have been used in the past to describe the radiation dose, but, at the International Radiological Conference held in Copenhagen in 1953, it was agreed that the unit of absorbed dose should be the rad. A substance is said to have received a dose of 1 rad when it has absorbed 100 ergs per gramme of material, from any kind of radiation. For engineering applications its multiple, the megarad, is more useful. This is equivalent to the absorption of 10 joules/g or 1·26 watt-hours/lb. Thus about 800 lb/h of material can be given a dose of 1 megarad for each kilowatt of power fully utilized.

Of the previous units, the most commonly used was the rep. This was invented to provide a unit, equivalent to the röntgen, but applicable to all forms of radiation, and has been widely used as a unit of dose. When so used, 1 rep can be taken as equivalent to 0·93 rad, but its use is deprecated.

Another unit that can cause confusion is that of radioactivity, i.e. the curie. This was originally defined in terms of the activity associated with 1 g of radium, but the latest definition is applicable to any radioactive material, and 1 curie of such material is that quantity which suffers $3{\cdot}7 \times 10^{10}$ disintegrations per second. Thus the curie is not a unit of power, as the energy released at each disintegration is not specified. The energy released is generally quoted in millions of electron-volts and the unit of power is the MeV-curie. Since 1 eV is equivalent to $1{\cdot}6 \times 10^{-12}$ ergs, 1 MeV-curie is equivalent to 5·9 mW. Table 1 gives the γ-ray energy released by some of the more suitable radioactive isotopes, together with the number of curies needed to provide 1 kW gross power.

Table 1

RADIOACTIVE ISOTOPES FOR IRRADIATION

Element	Isotope	Number and energy of γ-ray quanta produced per 100 disintegrations		Half life	Kilocuries needed for 1 kW gross power*
			MeV		
(*a*) *Long life*					
Cobalt ..	Co_{60}	100	1·17	5·6 years	68
		100	1·33		
Caesium ..	Cs_{137}	92	0·66	33 years	260
(*b*) *Short life* (use in reactor loop)					
Sodium ..	Na_{24}	100	1·38	15 h	41
		100	2·76		
Manganese	Mn_{56}	20	2·06	2·6 h	96
		30	1·77		
		100	0·82		
Indium ..	In_{116m}	25	2·09	54 min	68
		21	1·49		
		75	1·27		
		54	1·08		
		25	0·46		

* Neglecting self-absorption.

Data from: HOLLANDER, J. M., PERLMAN, I., and SEABORG, G. T.: 'Table of Isotopes', *Review of Modern Physics*, 1953, 25, p. 469.

(3) APPLICATIONS

The main applications for irradiation can be divided into two classes: one in which it is desired to change the molecular composition of a material to alter its properties, and the other in which it is desired to affect some impurity or unwanted part without appreciable effect on the main body of the material.

The first class includes polymerization and cross-linking of plastics, including the formation of copolymers, vulcanization of rubbers, halogenization of aromatic compounds and other chemical effects.

The second class includes sterilization of pharmaceuticals, preservation of food, disinfestation, and prevention of sprouting of potatoes and onions.

(3.1) Polymerization and Cross-Linking of Plastics

Large doses of radiation can cause polymerization and cross-linking in plastics.[2, 3] Doses needed are of the order of 5–100 megarads.

Polythene, when fully cross-linked, no longer melts, and it remains as a rubber-like solid up to a temperature of about 350° C, and resists organic solvents. Although the development of high-temperature polythenes has made irradiation unnecessary in a number of applications, it is still needed for temperatures over 125° C or for use in oils. The main applications of irradiated polythene so far are for small parts, such as valve holders, containing inserts which have to withstand the heat of soldering, and for cables and tapes. Polythene-insulated wire and wrapping tapes are available commercially in this country and the United States.[4, 5] Graft polymerization, in which a monomer is polymerized in contact with a different polymer, forming an intimate bond, is also possible by means of irradiation. Possible applications are the bonding of a layer of styrene to polytetrafluorethylene to improve the adhesive properties. Other examples are given in Reference 6.

Some other plastics, such as p.v.c., degrade when subjected to large doses of radiation.

(3.2) Vulcanization of Rubbers

Vulcanization is a form of polymerization, and both natural and synthetic rubbers can be vulcanized by irradiation.[7] The chemical agents needed for heat vulcanization are not required and a better product results. It is reported that motor tyres vulcanized by irradiation have 10% greater abrasion resistance than ordinary tyres.[8] Silicone rubbers can be vulcanized easily and rapidly by irradiation.[9]

(3.3) Chemical Reactions

Many chemical reactions can be initiated by radiation. For example, when aromatic compounds are irradiated in the presence of halogens, addition products are formed. One process, the formation of γ-hexachlorocyclohexane, a powerful insecticide, by the irradiation of a mixture of benzene and chlorine, has been shown to be commercially attractive.[10]

If hydrocarbons are irradiated in the presence of sulphur dioxide and oxygen, sulphonic acids are produced, which are the bases for certain detergents.[11]

Other chemical processes, such as the cracking of hydrocarbons to produce improved fuels, are under investigation.[12]

(3.4) Sterilization of Pharmaceuticals

Considerable experimental evidence exists that doses of the order of 2–5 megarads will reduce the probability of finding a living organism by a factor[13, 14] of at least 10^{10}. Unless the initial contamination is excessive, such a reduction is acceptable as giving complete sterility, and electron sterilization has been applied commercially to eye-drops and surgical sutures.[15] Further applications are likely to follow slowly, as there is an understandable desire to make certain that there are no harmful effects. Some changes may be necessary to the relevant Food and Drug Acts before radiation sterilization can be applied widely.

The dose needed for sterilization causes only a small rise in temperature, and thus heat-sensitive drugs can be sterilized, as

an surgical instruments, dressings, blankets, etc., which would be damaged by heat.

(3.5) Preservation of Food

Probably more money is being spent on investigations into the possibility of preserving food by irradiation than on any other application, mainly owing to the programme of the Quartermasters' Division of the United States Army involving the expenditure of several million dollars.[16]

As with pharmaceuticals, foods can be effectively sterilized with doses of the order of 2–5 megarads, but such doses cause unacceptable changes of taste in most foods. Those least affected, namely, pork, poultry, vegetables and fruit, have been irradiated and fed to animals and human beings to determine any ill effects. So far none have been reported.[17] Lower doses, of the order of 50 000–500 000 rads, do not cause complete sterilization, but improve the keeping qualities of many foods, and may allow storage under chilled conditions, rather than deep freezing. Irradiation with low-energy electrons, which do not penetrate deeply, may be helpful in reducing the growth of moulds on fruit, without appreciable effect on the taste.

Potatoes and onions can be stored without sprouting if previously given a dose of about 10 0000–20 000 rads.[18]

(3.6) Disinfestation

Doses of the order of 50 000 rads are lethal for most insect pests, and any not killed by this dose do not reproduce. Most insect eggs are made infertile by even lower doses.[19] Food parasites can also be killed in this manner, such as trichina in pork, which requires doses of the order of 30 000 rads.[20]

(4) MEANS OF PRODUCTION OF RADIATION

(4.1) Electrons

(4.1.1) Direct Accelerators.

Direct accelerators are the simplest type of electron accelerators, and take the form of a high-voltage supply, which can be alternating, half-wave rectified, or smoothed direct current, connected between the anode and cathode of an evacuated tube. Shaping of the electrodes, or additional focusing electrodes, allow the accelerated electrons to be formed into a narrow beam which passes through a hole in the anode, which is usually at earth potential. It is then necessary to bring the electron beam through the vacuum envelope. At low energies, under 500 keV, any practical vacuum window will absorb a high proportion of the electron power. This causes difficulties with window cooling, as well as reducing the efficiency. The difficulty has been overcome in one equipment by focusing the beam to a very small diameter and passing it through a narrow tube between the vacuum system and the outside atmosphere.[23] This tube has a labyrinth system fitted with very-high-speed vacuum pumps, so that a low pressure can be maintained in the vacuum chamber despite the direct connection to the atmosphere.

At higher energies thin windows can be used. These reduce the effective energy by about 150 kV. The loss of efficiency is still noticeable, and thus special attention to window cooling is needed at high powers. For these higher-energy machines, the power supply usually takes the form of a resonant transformer or electrostatic generator.

The resonant-transformer accelerator, developed mainly in the United States,[22] uses an air-cored transformer excited at its resonant frequency, which is usually some multiple of the mains supply frequency. The accelerator tube is mounted in the centre of the transformer, as shown in Fig. 3(*a*). The transformer is contained in a steel tank filled with sulphur hexafluoride under pressure to prevent breakdown. An alternating voltage is applied to the accelerator tube, and current passes on alternate half-cycles. The resonant-transformer accelerators available commercially are given in Table 2.

The electrostatic generator most used is that due to Van de Graaff,[23] one form of which is shown in Fig. 3(*b*). A moving belt is used to transfer charge from a low-potential electrode to a high-potential electrode. An electron tube, similar to that

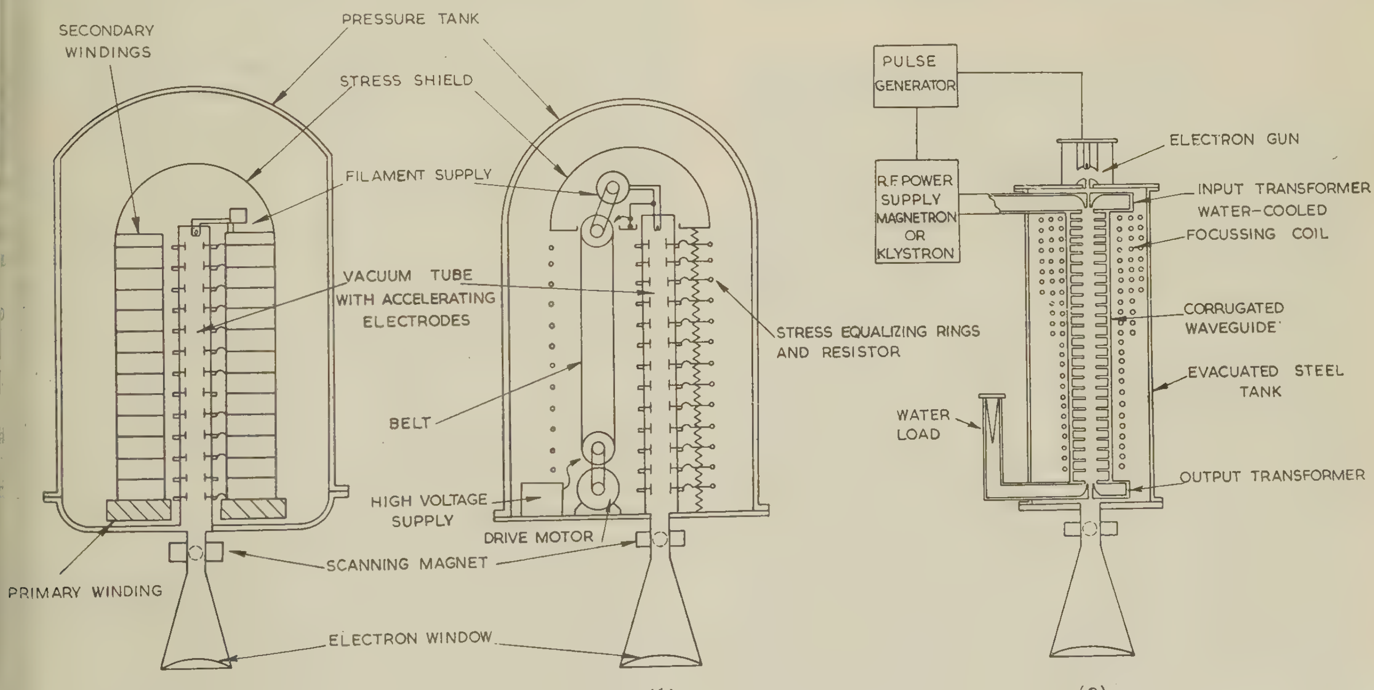


Fig. 3.—Principal components of electron accelerators.
(*a*) Resonant transformer. (*b*) Van de Graaff. (*c*) Microwave linear accelerator.

Table 2

ELECTRON ACCELERATORS AVAILABLE

Type	Maker	Electron energy	Mean power	Approximate price of accelerator	Approximate cost per kW*
		MeV	kW		
Resonant transformer	A	1	4·5	$69 000	£5 400[34]
		2	10	$120 000	£4 300[34]
		3·5			
Van de Graaff ..	B	1	0·25	$40 000	£57 000
		1·5	2·5	$50 000	£7 100
		2	0·5	$73 000	£52 000
		3	3	$130 000	£15 500
Linear accelerator	B	6·5	4	$194 000	£17 400
		9·5	4	$224 000	£20 000
	C	6	4	$145 000	£13 000[34]
	D	6	5	—	—
		10	5	—	—
		20	2·5	—	—
	E	4	0·8	£30 000	£37 500
	F	4	1	£30 000†	£30 000
		5	5	£50 000†	£10 000
		10	10	£90 000†	£9 000

* Conversion at $2.80 = £1 (neglecting import duty, taxes, etc.).
† The exact figure depends on equipment provided.
The figures are supplied by manufacturers unless references are given.

used in the resonant transformer, is connected between the high-potential electrode and earth. The steel container allows the whole equipment to be enclosed in a mixture of nitrogen and carbon dioxide at several atmospheres pressure to prevent breakdown. Van de Graaff generators have been constructed to produce voltages of the order of 8 MeV, but the limit for reliable commercial operation seems to be about 3 MeV, and the models commercially available are given in Table 2.

(4.1.2) **Indirect Accelerators.**

For reliable production of electrons with energies higher than about 3 MeV, indirect accelerators must be used, and these obtain the necessary acceleration without the use of very high potentials. The indirect accelerator which has made possible the provision of high powers at high electron energies is the microwave linear accelerator.[24] In one typical form, as shown in Fig. 3(*c*), electrons are accelerated by the axial field due to an r.f. wave travelling down a special waveguide at the same velocity as the electrons. Early accelerators used magnetrons[25,26] to supply the r.f. power needed, and were thereby limited to outputs of the order of 1 kW mean power, but very-high-power klystrons have now been developed for this purpose,[27] removing the limit on power that can be produced by a single accelerator. There is no fundamental limit to the energy attainable by a linear accelerator, but, as mentioned above, a practical limit for irradiation purposes may be set by the production of radioactive isotopes in the material being irradiated. The highest-power linear accelerator yet constructed was built for neutron research[28] and was designed for a power output of 30 kW at 25 MeV. This machine is made up of six sections, and a smaller number of sections would make a suitable irradiation source, such as 4 MeV 5 kW, 8 MeV 10 kW, etc. Variation in waveguide length and the number of klystrons makes it possible to produce a machine to fit almost any specification of energy and power likely to be required for irradiation. A number of linear accelerators are commercially available. Those known are listed in Table 2.

(4.2) **γ-rays**

The main sources of γ-rays for irradiation are the radioactive isotopes produced by nuclear fission or neutron bombardment.

(4.2.1) **Fission Products.**

When uranium 235 is split a large number of radioactive isotopes are produced, ranging from rhodium 106 with a half-life of 30 sec to caesium 137 with a half-life of 30 years. A full table of fission products is given in Reference 29.

There are several ways of utilizing the fission products:

(*a*) *Direct Irradiation in a Nuclear Reactor.*—The irradiation dose from neutrons would probably exceed the γ-ray dose, and there would be a great risk of induced activity in the material being irradiated.

(*b*) *Circulating Fuel.*—In a liquid-fuel reactor it would be possible to circulate the fuel, containing the fission products, through an irradiation chamber. Delayed neutrons may well be a serious problem, and the quantity of fuel required for the reactor would be increased considerably.

(*c*) *Gaseous Fission Products from a Liquid-Fuel Reactor.*—About one-third of the fission products are gaseous, and if the reactor uses liquid fuel, such as a solution of uranium salts in water, the gases can be removed and pumped to an irradiation cell. Most of the γ-rays radiated from the gaseous products are of low energy, below 0·5 MeV, and thus a large amount of the power would be absorbed in the double-walled container needed for safety.

(*d*) *Fuel Rods from Reactor.*—The fuel rods of a solid-fuel reactor become 'poisoned' with fission products after a while and have to be removed for re-processing. It is usual to store these under water for some months to allow the activity to fall to a low level before re-processing. Such rods have been used on a small scale, to provide experimental irradiation facilities. Most of the activity is due to short-lived isotopes, and thus the fall of activity with time is very rapid at first when the activity is high. The average energy is low (about 0·8 MeV) and the self-absorption in the rods is high, so that the available power is small. Transport of the fuel rods may be a problem which may be realized when the proposal described in Reference 29 is considered. Here an average of 76 fuel elements need replacing each week, and it is likely that each element would have to be transported separately in several tons of lead. The effective power of this facility is 4·9 kW.

(*e*) *Separated Fission Products.*—Potentially the most useful of the separated fission products is caesium 137. In this country it is separated as the sulphate salt with an activity of about 17 curies/g or about 30 watts/lb. Figures are not available, but it is thought that the annual production is not more than a few thousand curies. It has been estimated that, as a result of the power-reactor programme, the annual production[30] of caesium 137 should be 10^7 curies by 1965. If all this could be separated and concentrated it would be equivalent to a gross power of under 40 kW.

(4.2.2) **Radioactive Elements Produced by Neutron Bombardment.**

A number of elements can be made radioactive by neutron bombardment. Those most suitable for irradiation have a large cross-section for neutron capture and give high-energy γ-rays on disintegration. They can be divided into two classes, depending on whether the isotope has a short half-life, and so must be used at the reactor, or a long half-life, so that it can be used anywhere. In the first class the most suitable elements are sodium, manganese and indium, and in the second, cobalt. Particulars of the relevant isotopes are given in Table 1.

(*f*) *Sodium-Cooled Reactor.*—In a reactor cooled with liquid sodium, it would be possible to circulate the coolant through an irradiation cell, while the sodium 24, formed by neutron capture in the reactor, could provide the γ-ray source as it decayed back to the normal sodium 23. This need not interfere with the operation of the reactor, the radiation level would vary with reactor power level, but with a considerable time lag, owing to the 15-hour half-life.

(*g*) *Induced Activity in Circulating Liquid.*—If solutions of salts of manganese or indium are circulated first through a reactor and then through an irradiation cell, the manganese 56 or indium 116 produced by neutron capture in the reactor will decay in the irradiation cell with the production of the γ-rays shown in Table 1. A special reactor would be needed for optimum operation, and such a one was planned for the Quartermasters' Division of the United States Army, using indium-sulphate solution as the circulating material.[31] It is understood that initial estimates of the cost, given in Table 3, proved to be too low, and the project has been dropped. It is to be replaced by an irradiation facility[32] using cobalt 60.

(*h*) *Cobalt* 60.—The long half-life of over five years, the high activity possible, and the reasonably high γ-ray energy produced, make cobalt 60 the most suitable of all isotopes for irradiation, but the restricted facilities for its production and high cost reduce the probability of its becoming commercially attractive. The annual production of cobalt 60 in this country is not revealed, but the largest single source reported is one of 10 000 curies at Wantage.[33] The present published cost of cobalt 60 is about £2 per curie, or £140 per watt. It is believed that a source of 150 000 curies is due to be shipped to Australia for commercial irradiation. The current annual production of cobalt 60 in the United States is reported to be 300 000 curies, and the largest single unit outside Oak Ridge is one[32] of 62 000 curies, or about 1 kW. The cobalt 60 unit for the United States Quartermasters' Corps is planned to use about 2 megacuries, and production will have to be stepped up if that is to be achieved in a reasonable time. The present price of cobalt 60 in the United States is understood to be \$2 to \$9 per curie, depending on activity. Statements have been made that the price of cobalt 60 should come down to 6 cents per curie, but a more realistic survey estimates a minimum price of 35 cents per curie,[34] when produced in a special reactor. The latter figure represents \$24 000 per gross kilowatt.

The most detailed estimates published to date on the possible schemes for the use of radioactive isotopes for large-scale irradiation are given in a report of the Quartermasters' Division of the United States Army.[29] This considers all the schemes given above with the exception of that for cobalt 60. Table 3 gives a number of figures of interest taken from this report. Although the power in each case is quite high, the dose rate is very low, so that a large quantity of material is held up in the irradiation cell. The time needed for high doses, such as cross-linking polythene, would be several days even in the case of caesium 137, and would be over a month with the fuel-rod irradiator.

(5) PROBLEMS OF INDUSTRIAL APPLICATION

The main problems to be solved in applying irradiation sources for industrial use are those of achieving a uniform dose rate and maximum utilization of the radiation power available, dose measurement, and shielding and protection for personnel. Some of these tend to differ for γ-ray and electron sources, and will be dealt with separately. In addition, there may be problems of cooling of the material when subjected to large doses.

Table 3

ESTIMATES FOR FOOD-IRRADIATOR SCHEMES. (Data Taken from Reference 29)

Source	Gross power	Effective dose rate	Hold up of material	Capital cost per gross kW	Cost of irradiation per megarad/lb	Notes
	kW	rad/min	tons	$\$ \times 10^3$	cents	
Fuel elements	4·9	4×10^2	22	92	0·82	Fuel elements free. No transport charges
Gaseous fission products	50	5×10^3	17·5	13	0·14	Assuming suitable reactor available
Coolant loop. Sodium 24	24	$1{\cdot}5 \times 10^3$	28	29	0·26	Assuming free use of suitable reactor
Circulating indium solution	73	$1{\cdot}1 \times 10^4$	12	40	0·56	Special reactor. Neglecting cost of fuel
Caesium 137	22·6	$3{\cdot}5 \times 10^3$	12	17	0·15	Neglecting cost of caesium 137
Accelerator No. 1	7·5	$> 10^6$	Negligible	55	0·22	Including all equipment
Accelerator No. 2	50	$> 10^6$	Negligible	20	0·09	Including all equipment

(5.1) Sources

(5.1.1) γ-ray Sources.

The main difficulty in the efficient use of the power from γ-ray sources is that the power is radiated in all directions, and the intensity falls off exponentially with distance through the material. Most of the γ-ray units in existence were designed for experimental irradiation where uniformity of dose and relatively high dose rates over small volumes were of more importance than efficiency. These units usually have a number of sources symmetrically arranged around the irradiation space.[33] It is obvious that only a small cone of radiation from each source is used, the rest being wasted.

For any reasonable efficiency of utilization, the layout must be reversed, with the material to be irradiated surrounding the source. A high-power source must also be of large area, to reduce the losses due to self-absorption. Many of the schemes suggested in the literature[29, 35, 36] propose the use of plaques of radioactive material, with conveyor systems zigzagging between them in such a manner as to present both sides of the material to be irradiated, in order to even out the dose. The plaques consist of canned metal or salts in the case of cobalt and caesium, and a series of pipes in the case of liquid or gaseous materials. Nearly all the proposals deal with regular articles, such as meat packed in rectangular boxes, cans and sacks of bulk material. Under such conditions, most authors consider that a maximum of 25% of the net power from the source can be absorbed. Special cases can obviously be found where the efficiency could

be higher, but it seems a reasonable maximum for most applications. The optimum design of γ-ray sources is treated in detail in References 35 and 36.

(5.1.2) **Electron-Beam Sources.**

Most electron machines produce a small-diameter well-collimated beam. Usually, this beam is smaller than the object to be irradiated, and it is necessary to spread or scan the beam to cover a larger area. A typical electron accelerator produces

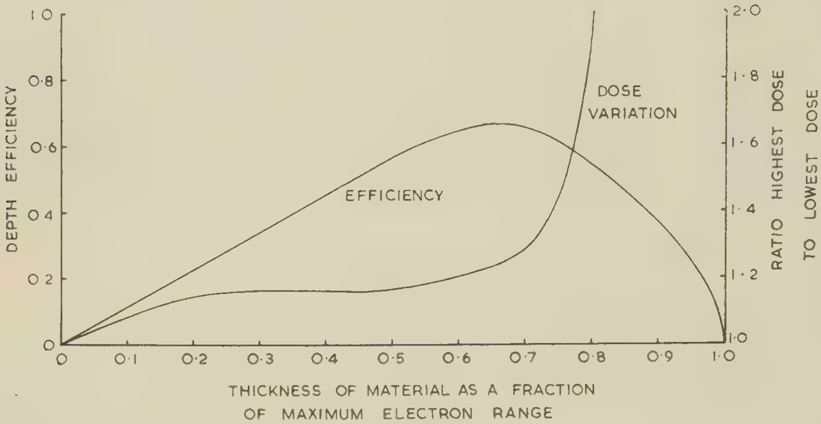


Fig. 4.—Depth efficiency and dose variation for electron irradiation from one side.
The curves are calculated for 10 MeV electrons; those for electrons in the range 5–15 MeV will be similar.

a beam of about 1 cm diameter. This beam can be brought out through a thin metal window, thick enough to withstand the atmospheric pressure. Such a window will absorb some power from the beam, and cause some scattering of the electrons. In early experimental work with electron machines, windows thicker than necessary were used, so that the beam was scattered over a large area. This meant that reasonably-sized articles could be irradiated fairly uniformly, but the efficiency was low, and such a scheme would not be suitable for industrial use. The most usual scheme is to spread or move the beam in one plane and traverse the object to be irradiated at right angles to the beam movement, so that the whole area can be irradiated. Methods of spreading and scanning are described later, and by careful design it is possible to achieve a uniform intensity of radiation over the area required. Owing to the variation of ionization with depth, as shown in Fig. 1, it is difficult to achieve a uniform dose rate throughout the material. Fortunately, it is the minimum dose in the material which is of importance for most processes, and it is no detriment if some parts have had a slightly greater dose.

Each kilowatt of radiation power is capable of giving a dose of 1 megarad to 800 lb of material per hour, if fully utilized. One practical case where full utilization is possible is that of a continuously agitated fluid, of greater thickness than the maximum electron range. In almost all other cases, some of the electron power must be wasted. The efficiency of utilization can be considered as the product of the area and depth efficiencies. This is strictly true only for non-divergent beams, and correction is necessary for large angles of scan.

The area efficiency is defined as the ratio of the area occupied by the material to the total area scanned, and will have to be assessed for each individual case. Efficiencies of over 0·9 can be obtained for bulk material, or regular rectangular objects where the width of the beam can be adjusted to be just greater than that of the conveyor or conduit. At the other extreme, with irregularly shaped objects that cannot be interlaced, or small quantities of material in large containers, this efficiency may be below 0·1.

The depth efficiency is defined as the fraction of the incident intensity which is absorbed in giving the required dose rate. This efficiency will vary with the ratio of the thickness of the material to the maximum electron range. For very thin specimens, most of the electrons penetrate and carry away a large proportion of their energy, resulting in low efficiency. For thick specimens, approaching the electron range, the average dose has to be increased considerably to ensure an adequate dose at the far side, and the efficiency is also low. Taking the 10 MeV curve from Fig. 1 as typical, a curve of efficiency against thickness in terms of maximum electron range has been calculated and is shown in Fig. 4. Maximum efficiency of 0·66 is obtained if the thickness of material is about two-thirds of the maximum range, and the highest dose is then about 25% greater than the lowest. For practical purposes, in the energy range of interest, it can be assumed that the optimum electron energy for a particular application is equal to $7 \cdot 5TD$ million-electron-volts, where T is the thickness in inches and D is the density of the material.

The depth efficiency can be increased considerably by irradiation from both sides with the appropriate energy. Fig. 5 shows the variation of dose with depth for a uniform material, of thickness 1·6 times the maximum electron range, irradiated from both sides. In this case the efficiency is 0·9, and the highest dose points are 16% above the minimum.

If the material is not uniform in thickness or composition, or if the material is in a container with thick walls, the efficiency is lower. This occurs in the case of sterilization of drugs in small

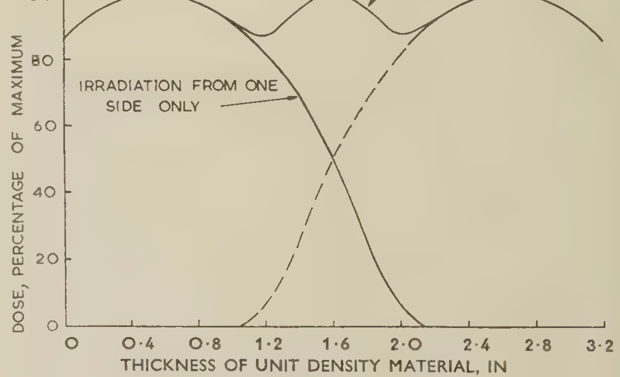


Fig. 5.—Dose curves for 10 MeV electrons.

phials. The electron energy must be sufficient to penetrate both the phial and the drug, but the power absorbed in the phial is wasted. When the electron energy required is appreciably above 10 MeV, the possibility of induced radioactivity should not be forgotten, although it has been shown that, even at 25 MeV, the problem is not serious.[37]

Taking both area and depth efficiencies into account, it can be seen that the maximum utilization efficiency for a uniform bulk material on a continuous basis is about 0·6 for irradiation from one side and 0·8 for irradiation from both sides. The efficiency for a particular case can be calculated from the geometry of the material, knowledge of the variation of dose across

the scanned area and depth-dose curves such as those of Fig. 1. If high accuracy is required, allowances must be made for differences of scatter at the boundaries of materials of different densities, and such calculations can be very complicated for irregular objects.

(5.2) Dose Measurement

Since the dose is defined in terms of absorbed energy, the primary measurement of dose can be made either calorimetrically, on materials that are not subject to chemical change on irradiation, or by consideration of the properties of the incident radiation and the absorption characteristics of the material.

Calorimetric methods of dose measurement present many difficulties, and it is unlikely that they would be used industrially. The intensity and energy of the incident radiation can be determined without great difficulty, and this method is frequently used.

Secondary dose measurements are mainly by irradiation of some material which undergoes a known chemical or other change under conditions as nearly as possible identical to those of the treated material.

(5.2.1) Intensity Measurements.

The intensity of radiation is defined as the energy flow through unit area. If an electron beam is uniform and of known cross-section, the intensity can be measured calorimetrically by absorbing the whole beam. At energies higher than 10 MeV errors can be caused owing to the production of X-rays. It is often more convenient to determine the intensity by measurement of incident current and electron energy. The total current can be collected by means of a Faraday cup of thickness greater than the electron range, and the energy measured by spectrometer. If the intensity over a given area is required, the current intercepted by a plate of the required area, and of thickness greater than the electron range, can be measured. A light material should be used to minimize back scattering, but even with aluminium some correction must be made at low energies. For example, at 4 MeV the correction is about 12%. A water target will give negligible back scattering for any energy above 2 MeV, but it may not be simple to use. A collector plate should be bordered by a similar material to reduce the effects of edge scatter. A useful device to check the uniformity of intensity of radiation over an area consists of a chequer-board of squares of aluminium plate separately insulated, and surrounded by a border of aluminium at least an electron range wide. A survey of the currents intercepted by each square will give an indication of the variation of intensity.

The intensity of γ-ray radiation is usually measured by means of ionization chambers.

(5.2.2) Absorbed Dose.

The absorbed dose depends on the intensity of radiation, its energy, the time of exposure, and the absorption characteristics of the material. In the case of an electron beam it is possible to calculate the dose at a given depth from the intensity and energy, using curves of the variation of ionization with depth. For example, consider the case of a beam of 10 MeV electrons, with a current density of 1 $\mu A/cm^2$. The intensity will be 10^8 ergs/sec per cm^2. The area under the curve for the absorption of 10 MeV electrons in water (Fig. 1) is $3 \cdot 85$ cm units, so that the power absorbed at the peak of the curve is $1/3 \cdot 85 \times 10^8$ ergs/sec per cm^2, or $0 \cdot 26 \times 10^8$ ergs/sec per gramme, for this case. The peak dose rate would therefore be $2 \cdot 6 \times 10^5$ rads/s.

Once the intensity has been determined, it is only necessary to ensure that the operating conditions remain the same when the measuring plate is replaced by the material to be irradiated. With pulsed accelerators, the beam can be passed through a pulse-current transformer, and the current monitored.

(5.2.3) Indirect Methods of Dose Measurement.

The most accurate of the indirect methods of measuring dose depend upon chemical changes, such as the oxidation of ferrous to ferric ions in sulphuric-acid solution.[38] Another depends on the reduction from ceric to cerous ions.[39]

Other effects used are the darkening of photographic film and paper, the decolorization of some dyes such as methylene blue,[40] the change of colour in chlorinated hydrocarbon-dye solutions[41] or gels, the colouring of glasses,[42] the change in ultra-violet-light transmission of certain plastics,[43] and the change in viscosity of a polymer.[44]

In most practical installations, the dose is estimated from the incident intensity and periodic checks are made with the ferrous-ferric or similar dosemeter. For some applications, such as the sterilization of drugs, where it is desirable to have some positive indication that each package has had at least the minimum dose, small indicators that can go through the process attached to each package are needed. Preferably such an indication should be obvious without needing apparatus to interpret it, such as a change in colour. Clear unplasticized polyvinyl chloride has been used for checking the dose received by pharmaceutical products.[45]

(5.3) Shielding and Protection of Personnel

By international agreement, a level has been recommended for the maximum stray radiation permissible in areas to which the public has unrestricted access. The level is that which would give a dose rate of $0 \cdot 75$ millirads/h. A higher level, $7 \cdot 5$ millirads/h, is permitted in areas of restricted access, but, for industrial purposes, it is desirable to have sufficient shielding to ensure that the stray radiation is below even the lower figure.

Several books[46, 47] have been written on the subject of shielding, which can set difficult problems owing to the very high attenuations required. Thus it is comparatively easy to achieve a dose rate of 20 megarads/sec in the beam of an electron accelerator which is over 10^{12} times that permissible outside the irradiation cell. Calculations for the thickness of shielding needed in the direct line of radiation are comparatively easy, and the main difficulty is in assessing the scattered radiation in other directions.

Almost any material can be used for shielding, but the denser the material, the less the thickness required. Concrete is the most popular of the structural materials, as it is usually the cheapest. Where minimum thickness is required, concrete can be loaded with barytes, iron ore or metallic iron, or sheets of iron or lead can be used. The cost of such materials rises at a greater rate than the density,[48] and so should be used only when the overall size is of importance, or for shielding a small volume.

(5.3.1) γ-ray Sources.

As the radiation is emitted in all directions, heavy shielding must be used all round a γ-ray source. For this reason most suggestions for large γ-ray irradiators propose an underground radiation chamber.

Curves for the shielding effect of concrete for the γ-rays from small sources of cobalt 60 and caesium 37 are published by the A.E.R.E.[33]

Extreme safety precautions would need to be taken with any commercial γ-ray irradiator, and maintenance of the conveyor and other equipment in the irradiation cell may prove difficult. Most proposals call for the removal of the γ-ray source into a storage chamber or pool of water, but in some cases where this would be difficult, remote removal of the conveyor system is

proposed.[29] All radioactive materials should be sealed in double-wall containers, with a liquid or gas circulated between the walls, and monitored continuously to detect any leakage of the radioactive material. This precaution is not necessary in the case of metallic cobalt, which can be sealed in aluminium cans, before conversion to cobalt 60 by neutron irradiation.

The problem of protecting personnel from their own carelessness is very great for γ-ray sources, since the source is silent and the radiation has no immediate perceptible effect. Any interlock systems should be mechanical, to be independent of power failure. The services of a qualified health physicist should be available at all times, and continuous monitoring is essential during all maintenance operations.

(5.3.2) Electron-Beam Sources.

The electron beam is stopped by a relatively thin layer of material, and usually the more serious shielding problem is set by the X-rays produced. The amount of X-radiation produced depends on the density of the material stopping the electron beam. Therefore anything in the path of the beam, such as the conveyor, should be of a light material, if possible, like aluminium, and an aluminium water tank is the best back stop.

The maximum thickness of shielding will be required in the direction of the electron beam. Fig. 6 shows the thickness of

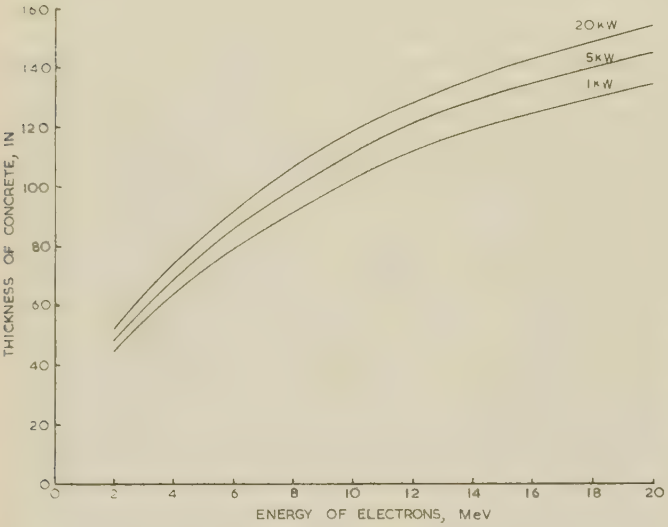


Fig. 6.—Thickness of concrete necessary in the direct line of the electron beam, assuming no back stop.

Narrow beam attenuation data obtained from Reference 46.

concrete required for the worst possible case, where the beam can impinge directly on the concrete shield. The thickness required tends to flatten out with increasing energy, and the shielding for a high-power high-energy machine should not be much more expensive than for a lower-power machine. If the beam direction is fixed, and an aluminium back stop is used, with local shielding, the thickness of concrete can be reduced. For example, with a 10 MeV 5 kW machine, the fitting of a back stop with 8 in of steel or 5 in of lead behind, and distant 3 ft from the shield wall, would allow a reduction in wall thickness from 110 to 75 in.

Estimation of the thickness of concrete needed in other directions is more difficult, as it is so dependent on both the electron and X-ray scatter from the material being irradiated, the conveyor, etc. Generalization is dangerous on such a subject, but about 3 ft less than that needed in the forward direction will usually be adequate.

It is usually more economical in shielding material to have the accelerator outside the irradiation cell, the beam passing through a hole in the shielding wall. Some X-rays will be generated in the accelerator itself, owing to stray electrons hitting parts of the internal structure, but the shielding round the accelerator can be much thinner than that round the irradiation cell.

The other problem is that of getting the material into and out of the irradiation cell without impairing the shielding. Some sort of labyrinth is needed, and this must be designed so that multiple scattering of both electrons and X-rays is taken into account. At least three, and preferably four, scatterings should be needed on any path out of the irradiation cell.

The problem of protection during maintenance is much easier with electron accelerators than with γ-ray sources, since the machines can be switched off, and, for those with a maximum energy of under 15 MeV, there is negligible residual activity. Even over 15 MeV, the activity produced in most materials likely to be irradiated is small and usually short-lived. Interlocks to prevent the operation of the machine when the irradiation cell is entered are usually adequate, but due regard to the skill of maintenance and test personnel in circumventing interlocks should be taken in their design.

(5.4) Heating Effect of Radiation

Almost all the energy absorbed by a material when irradiated eventually appears as heat. Thus when water is given a dose of 1 megarad, equivalent to 10 joules/g, or 2·4 cal/g, there will be a rise in temperature of 2·4° C.

For low dose applications, such as sterilization, this temperature rise is not important, except possibly in the case of heat-sensitive drugs irradiated in metal or glass containers. Owing to the lower specific heats, metals and glass undergo a greater temperature rise for a given dose, and if there is no appreciable heat loss, the temperature rise for aluminium is 11° C, for iron 22·5° C, for copper 26° C and for glass 15° C per megarad dose.

With γ-ray sources, owing to the low dose rate, heating of the radiation source from self-absorption would be a greater problem than heating of the material being irradiated.

Very high dose rates can be obtained from electron accelerators, and cooling can be a very real problem when high doses are required. For example, if a slab of polythene were given a dose of 25 megarads in a very short time, so that there was negligible loss of heat, the temperature rise would be 110° C and melting could occur before the polythene was sufficiently cross-linked to be stable. The thermal conductivity of polythene is so low that, even if the outside surface of a thick slab is kept cool, the inside can reach a high temperature if the dose rate is high.

The situation is much worse when a metal insert is included in a material of low thermal conductivity. Such a case is that of a continuous length of polythene-insulated copper cable which is to be given a dose of 25 megarads to cross-link the polythene. If the dose were given in a very short time, the rise in temperature of the copper would be over 640° C. Therefore, the cable must either be given a number of small doses with cooling periods in between, or irradiated continuously at a dose rate low enough for the heat generated in the conductor to escape through the polythene. In the first case, if a maximum polythene temperature of 90° C is allowed, and the whole cable is cooled to 20° C between doses, at least nine passes will have to be made. In the second case, it can be shown that, if the

outside of the cable is held at 20° C during the irradiation, the maximum permissible dose rate is

$$\frac{3 \cdot 8 \times 10^5}{D^2 \times d^2\left(17 \cdot 3 \log_\varepsilon \frac{D}{d} - 1\right)} \text{ rads/sec}$$

where D = Outside diameter of the polythene.
d = Diameter of the conductor (assumed solid).

For a radio-frequency feeder cable such as the type U.R.1 this gives a maximum dose rate of 3×10^5 rads/sec, or about $1\frac{1}{3}$ min for the 25-megarad dose. In the case of a polythene-insulated e.h.v. cable, $19/\cdot083$ in conductor with $0\cdot11$ in radial thickness of polythene, the maximum dose rate is $3\cdot5 \times 10^4$ rads/sec, or about 12 min for 25 megarads.

These figures assume that the electrons are of high enough energy to penetrate the cable completely. For cables with large conductors, some increase in permissible dose rate, and in utilization efficiency, can be obtained if the electron energy is chosen so that the range in polythene is only about $1\frac{1}{2}$ times the radial thickness of the polythene. The cable must then be rotated during irradiation, or an applicator must be designed to spread the beam so that the cable is irradiated uniformly all round.

(6) PRACTICAL APPLICATION OF ELECTRON IRRADIATION

(6.1) Machine Mounting

Once the questions of electron energy and power required have been settled from consideration of the factors dealt with in Section 5, the decision whether the beam should be vertical or horizontal must be made. From the shielding aspect, the vertical beam is very attractive, and would be chosen for most cases where irradiation from one side was sufficient, if no other factors influenced the choice. When irradiation is needed from both sides, it may be more convenient to use horizontal beams, especially if two machines are to be used.

A vertical beam can be obtained either by mounting the accelerator with its axis vertical or using a magnet system to bend the beam from a horizontally-mounted machine. In the latter case, if the bending system uses an electromagnet, its supply should be interlocked with the accelerator, so that it is impossible to switch on without the beam deflected unless provision for this has been made in the design of the shielding.

(6.2) Beam Spreading or Scanning

Mention has been made in Section 5.1.2 of the necessity for spreading or scanning the electron beam in one plane while traversing the material to be irradiated in the other plane. The most usual method is to scan the beam by deflecting it across the width of the material. This arrangement is shown in Fig. 3. The electron beam passes between the poles of an electromagnet, which produces a varying transverse magnetic field. The electrons are deflected at right angles to this field, pass down the flare and through the thin window. The window should be close to the material so that the effects of scattering in the window are minimized. Magnetic deflection is shown, as that is usually more convenient, and can be achieved with relatively low magnetic fields. Electrostatic deflection requires the use of very high electric field strength. For example, similar systems for a 4 MeV electron accelerator require peak fields of 350 gauss or 100 kV/cm for the two cases. It is not usually convenient to place the deflector magnet inside the vacuum envelope, and thus the latter must be non-magnetic, at least locally, and of high resistivity, in order to minimize the eddy-current losses. For uniformity of irradiation, a sawtooth scan is ideal, but one of triangular form is satisfactory if the speed of scan is fast compared with the speed of the object, so that there is appreciable overlap. In the case of machines such as the linear accelerator, which deliver the electrons in short pulses, there is an additional problem. For example, if the pulse-repetition frequency is 500 pulses/sec and the scanning frequency 50 c/s, there will be only ten pulses per scan. If the two frequencies are locked together, and the width of the object is greater than five times the diameter of the electron beam, there will be considerable variation of dose across the object. This can be overcome by the choice of a suitable non-integral ratio between the two frequencies, but only if the movement of the object per scan is small compared with the beam diameter. This may present difficulties when using a high-power machine for giving low doses, but it can be overcome by using the spreading technique described below, or moving the object further from the window, to increase the effect of scatter in the window and the intervening air, at some small loss of efficiency.

An alternative to scanning the electron beam is to spread it into a line by the electrical equivalent of a cylindrical lens. If an initially parallel electron beam is passed through a quadrupolar magnet, as shown in Fig. 7, electrons off the axis in the x-plane are deflected inwards and brought to a focus, and those in the y-plane are deflected outwards. If a second identical quadrupole is placed at a distance equal to twice the focal length from the first, the electrons in the x-plane will be brought back to a parallel beam and those in the y-plane will be deflected farther outwards. Thus the beam of electrons comes through the lens system unchanged in one plane and spread in the other. It should be noted that, in this application, the two quadrupoles are of similar polarity, and not of opposite polarity as used in the alternating-gradient focusing system.

If there is a variation of intensity across the original beam, it is reproduced across the spread beam, and additional magnets are needed to even this out. Their action can be seen from Fig. 8. The spread is made greater than required, and the additional magnets are used to deflect the outermost electrons to reinforce the lower levels. Similar spreading can be achieved with non-uniform magnetic fields in bending magnet systems.[49]

If irradiation is needed from both sides, using a single accelerator, solid objects of reasonable size can be irradiated, turned round and irradiated again. With liquids or bulk material it is not always possible to prevent relative motion between the container and its contents. To overcome this

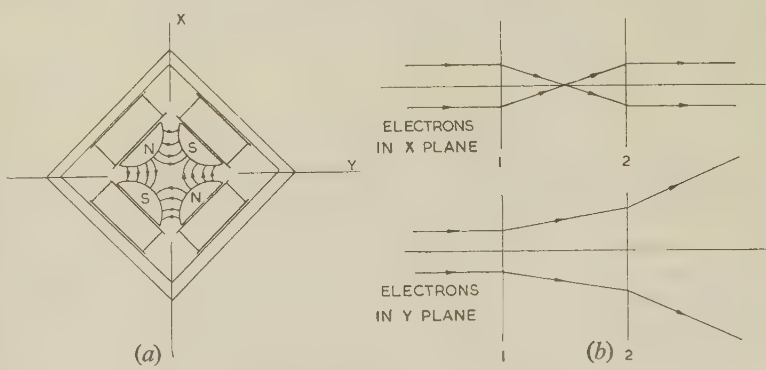


Fig. 7.—Electron-beam spreading.

(a) Quadrupole magnet system.
(b) Deflection of electrons by two identical quadrupole magnets.

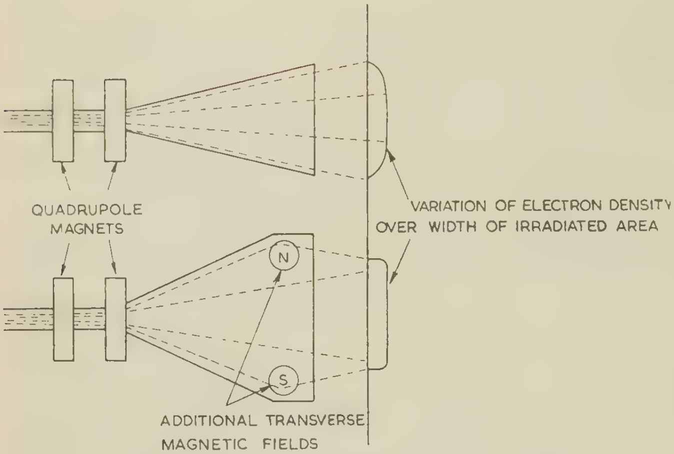
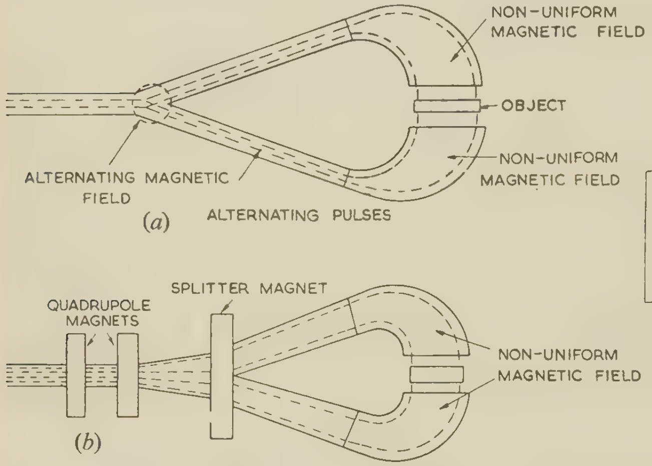
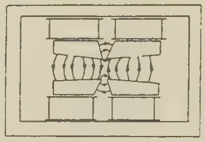


Fig. 8.—The use of additional magnets to improve the uniformity of electron density from the beam-spreading system.





(c)

Fig. 9.—Systems for irradiating material from both sides.
(a) Switched beam. (b) Split beam. (c) Splitter magnet.

difficulty the beam can be either split or switched and directed to both sides of the object. Switching is the easier method with pulsed machines, since an electromagnet, with field varying at half the repetition frequency, can be used to switch alternate pulses into two channels. Bending and scanning or spreading magnets then allow the whole area of the object to be covered. Such an arrangement is shown in Fig. 9(*a*). Beam splitting is best achieved after spreading, as shown in Fig. 9(*b*), which shows the form of the splitter magnet at (*c*). With high-energy electron beams, where air scattering is not excessive over short paths, a combined splitting and bending magnet can be used with a scanned beam.[50]

(6.3) Irradiation Chamber

The main problems in the design of the irradiation chamber are those concerned with getting the material into and out of the chamber without impairing the shielding.

(6.3.1) Fluids.

The simplest case is the irradiation of a fluid which can be pumped through a pipe through the chamber. It is only necessary to introduce a few bends into the pipe where it passes through the shielding walls. The problem of windows for irradiating fluids in pipes is discussed in Reference 50. Some solid bulk materials, such as grain, can be transported pneumatically through pipes, and can thus be treated as fluids for irradiation purposes.

(6.3.2) Continuous Films and Cables.

For those films and cables where the thickness is small compared with the electron range, it is necessary to irradiate a number of thicknesses simultaneously to achieve maximum efficiency. A system of rollers, as shown in Fig. 10, can be used for film material, and a series of pulleys for cables. In the latter case the layers should be staggered. By suitable design, the utilization efficiency can be high, since the film or cable is irradiated from both sides. The channels into and out of the radiation cell can be quite small, and as the material can be bent through a small radius, the labyrinth can be small. With larger cables, where the thickness is comparable with the electron range, it may still be necessary to use multiple passes to avoid overheating, as mentioned in Section 5.4. The minimum permissible radius of curvature for bends in such a cable may be large, and one way of overcoming the problem is shown in Fig. 11. In this, a series of grooved rollers constrain the cable to follow a path first through the beam, then through a trough of water or other cooling liquid and back through the beam. For maximum efficiency it may be necessary to irradiate the cable from both sides with comparatively low-energy electrons, and such an arrangement is shown. The size of loop necessary and the number of turns can be calculated from the data in Section 5.4, the dose required, and the rate of production of the cable.

(6.3.3) Solid Regular Objects.

It will usually be necessary to use a conveyor system for solid objects, and the size and shape of the irradiation chamber and labyrinth will largely be determined by the dimensions of the objects and the electron-beam direction. In some cases, as with the food boxes studied in Reference 30, it is possible to fit a harness to

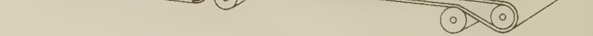


Fig. 10.—Irradiation of multiple layers of film material.

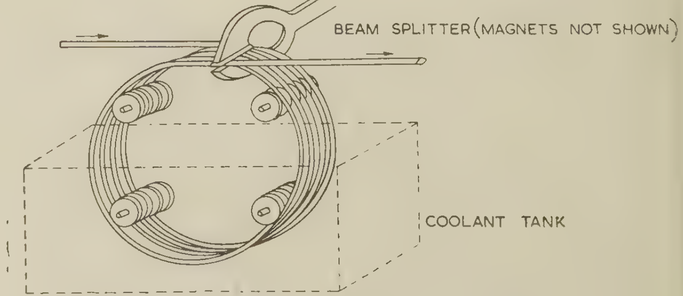


Fig. 11.—Irradiation of large-diameter cable.

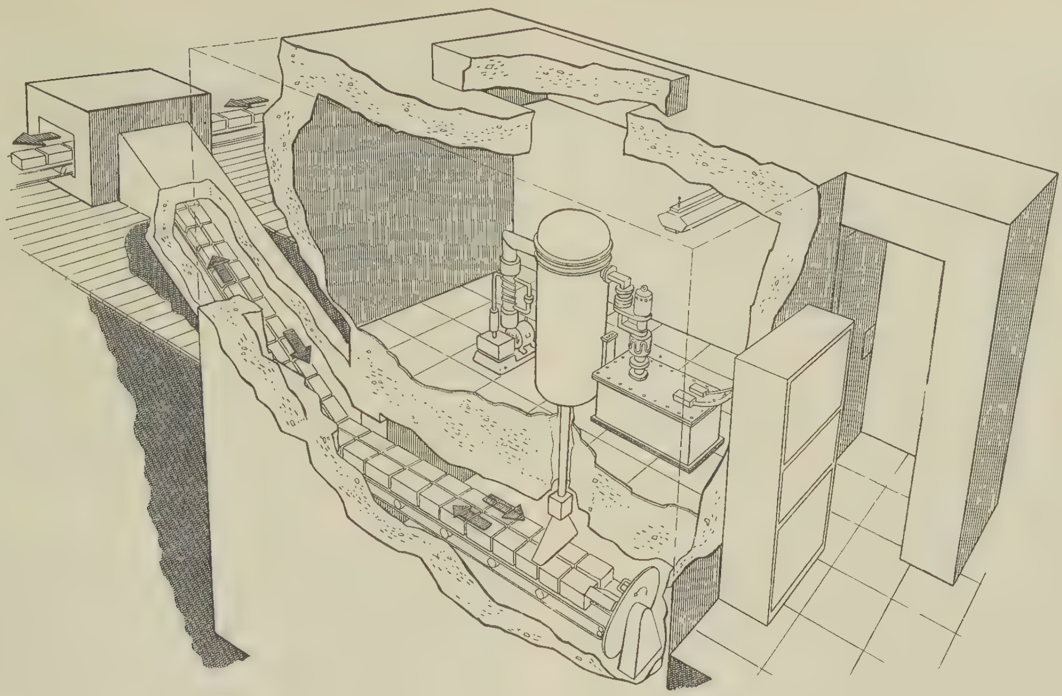


Fig. 12.—Installation for the irradiation of boxes on a conveyor system, using an electron linear accelerator.

each object, in order to enable the conveyor system to perform more complicated evolutions and thus allow a reduction in overall size of the labyrinth.

Fig. 12 gives an artist's impression of an irradiation unit suitable for incorporation in a production line. In this case rectangular boxes require irradiation from both sides. The boxes are transferred to a conveyor which takes them down to the underground irradiation chamber. The boxes are then taken through the beam from a linear accelerator at a controlled speed, turned over by a rotary device at the end of the conveyor, and back again through the beam, which is spread to cover both conveyors. A further conveyor takes the boxes back to the main production line. The accelerator is mounted above the ground in a shielded room. A typical 6 MeV 5 kW linear accelerator is shown, with the klystron valve which supplies the r.f. power, and the vacuum pumping system. The modulator and power supply unit, and the control rack, are outside the shielded area.

A layout for the use of two horizontally mounted accelerators for simultaneous irradiation from two sides is given in Reference 51.

There are obviously a large number of variations possible in the layout of the irradiation chamber and conveyor system, depending on the material to be irradiated and the ingenuity of the designer. However, a number of basic precepts should be borne in mind when considering a design:

(*a*) The labyrinth system should ensure that no direct path exists for any emergent radiation unless it has been scattered at least three and preferably four times.

(*b*) If possible, there should be a continuous barrier to absorb the scattered electrons. Where this is not possible, such as where conveyor systems pass through, the space round the conveyor should be blocked up, leaving the minimum aperture for the objects to pass through.

(*c*) Pure aluminium is the best material to use in places where it may be struck by the electron beam.

(*d*) If material of greater strength is needed, stainless steel is probably the best, and it can be used in the form of an open mesh for conveyor belts.

(*e*) Metals to avoid if the electron energy is over 10 MeV are copper, silver, zinc and tin. All these have the threshold for the production of radioactive isotopes in the range 10–20 MeV, with half-lives[52] of the order of 10–40 min. This might prevent immediate access to the irradiation cell after switching off.

(*f*) If possible, no organic materials should be used in the irradiation chamber, as these are eventually degraded by irradiation, even though some, such as polythene and polystyrene, are improved at first. Mineral-insulated cable should be used for all wiring.

(*g*) Bearings on the conveyor which carries the material through the beam should preferably be of graphite or graphite-impregnated sintered metal. Special greases have been developed which will withstand doses of about 10^9 rads, and it may be possible to use these for bearings outside the main beam area.

(*h*) When the electron beam passes through air, ozone and the oxides of nitrogen are formed. It is usual to fit a ventilating system to remove this contamination and discharge it where it will do no harm. When irradiating food, it might be desirable to refrigerate the irradiation chamber. To obviate the need for a ventilating system in such circumstances, it has been suggested that the ozone could be absorbed chemically.[29]

(7) ECONOMICS OF IRRADIATION

The factors of greatest interest, from an economic point of view in planning an irradiation unit, are the capital cost of the equipment per kilowatt of useful power, and the running cost per kilowatt-hour, or per megarad-lb of potential dose.

(7.1) Electron Accelerators

Figures are available to make accurate estimates of the costs of irradiation using existing accelerators, and an estimate can be made as to the future trend. The capital cost of available machines is given in Table 2, and it can be seen that this varies between £4 300 and £57 000 per kilowatt.

Taking a 5 MeV 5 kW linear accelerator as typical of the type of machine suitable for large-scale irradiation, the author has made an estimate of the cost of various irradiation processes.[53] The various items contributing to the running costs are given in Table 4, from which it can be seen that the overall cost is 27s. per kilowatt-hour, or 0·4d. per megarad-lb. This is assuming operation for eight hours per day, five days a week. Continuous

Table 4

RUNNING COST OF ELECTRON ACCELERATOR

Capital cost		*Hourly running costs*	
5 MeV 5 kW linear accelerator	£50 000	Klystron replacement	15s. 0d.
Building and conveyor	£20 000	Modulator valves	10s. 0d.
Spares	£4 000	Other valves and components	5s. 0d.
	£74 000	Skilled maintenance (part time)	3s. 0d.
		Miscellaneous ..	3s. 6d.
		Electric power 42 kW at 1d.	3s. 6d.
			£2 0s. 0d.

Total costs (per hour)

	40 hours per week	*Continuous service*
Depreciation on capital 10-year basis	£3 17s. 0d.	19s. 3d.
Interest on capital, 5% on £37 000	18s. 6d.	4s. 6d.
Running costs	£2	£2
Total ..	£6 15s. 6d.	£3 3s. 9d.
or	£1 7s. per kW/h	12s. 9d. per kW/h
Equivalent to about	0·4d. per megarad-lb.	0·2d. per megarad-lb.

Table 5

THE COST OF IRRADIATION USING A 5 kW ELECTRON LINEAR ACCELERATOR

Process	Typical dose	Estimated utilization	Capacity of 5 kW machine per hour	Approximate basic cost of treatment*
	megarad	%		
Prevention of sprouting (potatoes)	0·01	50	90 tons	1s. 6d. per ton
Disinfestation of grain	0·05	80	28 tons	4s. 8d. per ton
Preservation of foodstuffs	0·05†	45	16 tons	8s. 6d. per ton
	0·5‡	45	3 600 lb	½d. per lb
Sterilization of drugs	2	80 (in bulk)	1 600 lb	1d. per lb
		5 (in phials)	100 lb	1s. 4d. per lb
Vulcanization of rubbers	5	80 (in bulk)	640 lb	2½d. per lb
		25 (mouldings)	200 lb	8d. per lb
Treatment of plastics	25	80 (in bulk)	130 lb	1s. per lb
		25 (mouldings)	40 lb	3s. 4d. per lb

* Machine running 8 hours per day, 5 days per week.
† Low dose.
‡ High dose.

operation would reduce the cost to about 13s. per kilowatt-hour, or 0·2d. per megarad-lb. Even at the higher figure, the cost of treatment is quite low for many applications, and Table 5 shows the cost and quantity of material that can be treated per hour, for a number of cases. Other estimates[29, 34, 54] put the cost of electron irradiation at 0·08–1·0d. per megarad-lb, depending on the size and type of machine.

Future developments are likely to result in the simplification of the existing sizes of machines, and the production of larger machines, which should bring down still further the cost of treatment.

(7.2) γ-ray Sources

It is much more difficult to make an estimate of the cost of irradiation from γ-ray sources, since there is, at present, no source large enough to be of industrial importance, although at least one is under construction.

Owing to the low dose rate and consequent long hold-up time, the irradiation cells for isotope sources would have to be very large and the conveyor system quite complicated. In addition, some equipment must be provided for handling the source and removing it when maintenance or recharging is required. Because of the high capital cost of the cell and such equipment, estimates show that, even if the isotopes were to be given away free of charge, the cost of using them would probably exceed the present-day cost of irradiation with electron beams, except for very-low-power installations.

(8) CONCLUSION

The potential success of many processes involving the use of irradiation was demonstrated at least five years ago; the techniques for the production and application of the radiation have been developed, and it can be produced at an economic price. However, the number of industrial installations is very small. Those known to the author are given in Table 6A.

The reasons for the slow growth of industrial irradiation seem to be as follows:

(*a*) The reluctance of industrial organizations to incur the capital cost until someone else has proved the process on a large scale.
(*b*) High-power machines with the high energy necessary to penetrate a reasonable depth of material have only recently become available.
(*c*) A number of applications, such as the sterilization of drugs, may require change in Laws and Regulations to enable radiation processes to be used.
(*d*) Fear of the discovery of new chemical processes which might render irradiation unnecessary.
(*e*) Unrealistic statements about the low cost and availability 'in the near future' of large isotope sources.

In order to overcome, at least partly, the first difficulty, a centre for pilot-production irradiation has recently been opened.[55] Manufacturers can try out suitable processes on a small scale without the capital expense of purchasing a machine. Other units equipped with conveyor systems and available for pilot production are given in Table 6B.

Table 6A

INDUSTRIAL INSTALLATIONS

7 MeV 3 kW linear accelerator (Reference 15)	Sterilization of surgical sutures
2 MeV 1 kW Van de Graaff (Reference 56)	Sterilization of drugs
1 MeV 5 kW, 2 MeV 5 kW resonant transformers (Reference 56)	Cross-linking of plastic wire coating and strip
1 MeV 5 kW resonant transformer (Reference 56)	Cross-linking of plastics
1 MeV 5 kW, 2 MeV 10 kW resonant transformers (Reference 56)	Manufacture of Irrathene

Table 6B

INSTALLATIONS WITH CONVEYOR SYSTEMS SUITABLE FOR BATCH OR PILOT PRODUCTION

4 MeV 0·6 kW linear accelerator (Reference 55)	Rental for all processes
2 MeV 0·5 kW Van de Graaff (Reference 57)	Cross-linking of plastic wire coating and strip
2 MeV 0·6 kW Van de Graaff (Reference 57)	Cross-linking of plastic wire coating
4 MeV 2 kW linear accelerator	Rental for all purposes
3 MeV 3 kW Van de Graaff (Reference 56)	Treatment of plastics
2 MeV 0·5 kW Van de Graaff (Reference 56)	Rental for all processes
8 MeV 1 kW linear accelerator (Reference 56)	Rental for all purposes
8 MeV 2·5 kW linear accelerator (Reference 56)	Rental for all purposes

A number of the processes for which irradiation is suitable, such as the disinfestation of grain, the prevention of sprouting of potatoes and the vulcanization of silicone rubbers, can already be carried out by chemical means, but it can be shown that, for large quantities, irradiation can be the cheaper method.

It is likely that electron accelerators will become simpler and more powerful in the future, and tend to reduce the cost of irradiation still further. On the other hand, if the experiments to produce power from fusion reactions are successful, present estimates of future supplies of isotopes may have to be reduced. The isotope power available may have to be reserved for special cases where material of considerable thickness needs to be irradiated.

(9) ACKNOWLEDGMENT

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DISCUSSION BEFORE THE INSTITUTION, 5TH NOVEMBER, 1959

Mr. S. Jefferson: I should like to put forward some of the advantages of radioactive isotopes as sources of radiation, and to state that supplies and prices have changed for the better quite recently. It is now possible to negotiate with the U.K.A.E.A. for the delivery of megacurie quantities of cobalt 60; a kilowatt source of γ-ray energy now costs about £20 000, which puts it on a par with electrical machines.

Electrons from accelerating machines are to a large extent

complementary to the use of radioactive isotopes. For surface treatments electrons are sometimes more convenient when their limited penetration is no serious disadvantage. In many manufacturing processes, however, penetration is almost essential. Greater penetration can be achieved by increasing the quantum energy of the electrons, but above 10 MeV, photo-neutron generation occurs in sodium, chlorine, iron, phosphorus and carbon, with consequent radioactivation of most elements present. Cobalt 60 radiation causes no radioactivation.

Handling very large sources is not hazardous, provided that quite straightforward engineering principles are employed; in sending the sources to Australia, two $8\frac{1}{2}$-ton transport shields each carried 75 000 curies of cobalt 60, and would have been able to carry 100 000 curies each.

γ-radiation is proving valuable in sterilizing medical equipment made from cheap thermoplastics. One hospital group reports that, before using radiation-sterilized catheters, there was a very high incidence of bladder infection, but that, since using them, there has not been a single case.

Figs. A and B show a package irradiation plant at Wantage

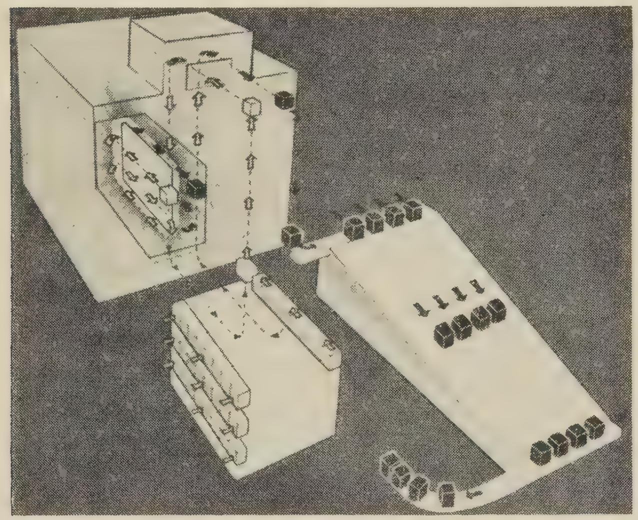

Fig. A

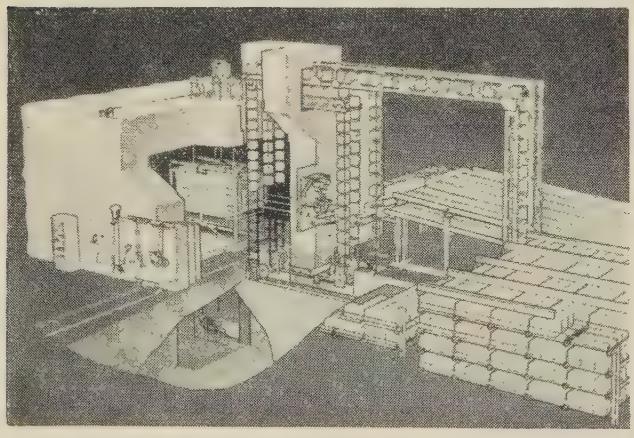

Fig. B

which is nearly complete and will use initially 150 000 curies of cobalt 60. Fig. A is a schematic of the plant, while Fig. B shows more detail. The source is loaded in a water tank which is built into the floor of the irradiation cell. The source is shown in its submerged position. When all is ready the irradiation cell is vacated and the source is raised to the middle of the irradiation machine where it is surrounded by the material being treated.

Dr. C. W. Miller: In reading the paper I was reminded of the first irradiation which the author and his colleagues carried out almost ten years ago. Using the electron beam from an 8 MeV linear accelerator, some very simple experiments indicated that sterility could be obtained in a variety of pharmaceutical products. It must be disappointing to the author that there should be such a long delay before widespread industrial application. It is perhaps worth remembering that in 1896, a year after Röntgen discovered X-rays, Minck published in Munich a paper 'On the question of the effect of Röntgen rays on bacteria and the possibility of their eventual application'. I do not know whether he lived to see any application, but I believe that the present author will live to see many of the applications mentioned in the paper used in industry.

Table 1 gives a comparison of the curie values of radioactive sources and the power output of those sources in kilowatts. For many years we have heard of sources measured in kilocuries and even megacuries; these are very large numbers. In this context, however, the curie is a small unit, and it is interesting to see the figure of 68 000 curies/kW for cobalt 60. One at once does some conversions to assess the sources at the Wantage irradiation unit in terms of power output. There are several 10-kilocurie sources of cobalt, i.e. several 150-watt units. Fig. A shows package irradiation units of a few kilowatts and we know of the pond with the fuel rods. Perhaps what is not generally known is that, for several years, this unit has also had a linear accelerator rated at $1\frac{1}{2}$ kW and capable of about 2 kW.

I agree with Mr. Jefferson that machines and radioactive isotopes each have their own part to play, but we should not underestimate the penetration of electrons.

A further question is that of induced radioactivity, but this difficulty should not be overestimated. In almost all cases which I have investigated or of which I am aware the induced radioactivity would be no bar to the use of high-energy electron machines.

A further application of irradiation has not been mentioned. In a paper by Harlen *et al.** it has been shown that irradiation of certain long-chain polymers removes side branches which can then be collected under vacuum and subjected to analysis with a mass spectrometer. This is a very powerful tool in characterizing these side chains, and, so far as I know, the only way in which the side branching of a long-chain polymer can be determined.

In conclusion, the supply of sources of irradiation, be they isotopes or machines, has now reached the stage where industrial application is quite feasible. This seems to be a case where the engineer and the physicist have done their job and are anticipating the demands of the chemists and the food technologists, etc., who must still assess the value of the various processes.

Mr. T. R. Manley: There is no doubt that the discovery of methods of polymerizing ethylene using catalysts has scotched a promising application for large quantities of radiation. On the other hand, because polymers prepared by radiation are free from traces of catalyst and thus have improved properties, especially with respect to electrical properties, this has stimulated work on materials hitherto rejected. For example, the polysulphone groups of thermoplastics, made by the action of sulphur dioxide on olefins, attracted attention many years ago,† but, being considered inferior to other thermoplastics, they were neglected. Recently it has been found possible to polymerize

* HARLEN, F., *et al.*: *Journal of Polymer Science*, 1955, **18**, p. 589.
† British Patent No. 11635.

polysulphones using small radiation doses (0·7 megarads for 90% conversion) and they are once more being investigated.*

Other polymers which may well be produced by radiation are the fluorocarbons. Since the yields in this reaction are low,† these compounds would be expensive. In the past, however, the excellent properties of fluorocompounds have enabled them to find uses in spite of their high cost.

I should like to know about the availability, cost and efficiency of machines smaller than those mentioned in the paper. There are several instances where irradiated materials would be useful for curing silicones or vulcanizing rubber, but where the number of items involved would not justify an expenditure of £70 000. Such small machines might also find applications in the curing of resins used for encapsulating small electronic equipment. One of the difficulties with present resins is that components may be damaged by the exothermic curing reaction of the resin; by using radiation to cure these resins at low temperatures this difficulty could be overcome. Precautions would, of course, have to be taken not to irradiate transistors and other material whose characteristics are altered by radiation. This method would also permit the use of other resins, e.g. methacrylates, which, at present, are ruled out because of this exothermic reaction.

Mr. G. Saxon: The question of radioactivity induced during electron irradiation has been raised in the discussion, and it is time the matter was viewed in its proper perspective. The two lowest-energy photonuclear reactions, namely those with beryllium and deuterium, have been instanced. In the case of beryllium the product has a half-life of the order of 10^{-14} sec, and so any activity from this source would very soon become negligible. With deuterium there is no radioactive product.

I have carried out a calculation of the activity likely to be induced in 500 lb goat-hair bales when given a sterilizing dose 25 MeV electrons. Hair is a typical organic material containing carbon, oxygen, nitrogen, hydrogen, sulphur, etc., but the only serious activity produced would be radioactive carbon. It was estimated that a radiation level of about 1 rad/h would occur at the bale surface immediately after irradiation, but, in view of the 20 min half-life, the intensity would decrease to the background level after a 6-hour storage period. The threshold energy for the photonuclear reaction with carbon is 18·7 MeV, so that, with irradiation below this energy level, there would be no hazard whatsoever due to carbon.

Similar conclusions have been drawn by American workers* who calculated and measured the effect of irradiating various foods with 25 MeV electrons. Only carbon 11 and chlorine 34 were produced in quantities considered hazardous, and their radioactivities became negligible after a few hours' storage.

Finally, there is a possibility of activation by neutrons if a cooling pond is used as an irradiation source, and I should like to know whether the effect of this has been estimated.

Mr. S. Jefferson: In the 2 MeV region there is not much radioactivation; the more important cross-sections occur in the region of 10–15 MeV.

A fuel-element pond can only be operated conveniently near a reactor. The half-life of a decaying fuel element is changing all the time because it is made up of the half-lives of all the fission products, many of which are very short. It is also difficult to achieve a high efficiency in a water pond.

Mr. W. J. Brown: What is the efficiency of the package unit shown in Figs. A and B? What fraction of the radiation goes into the packages? Secondly, is it possible to make any statement about the cost of the treatment? We might think of unit-density material and 24-hour duty.

Mr. S. Jefferson: The efficiency with unit-density material will be about 30%, but this is an approximate figure because, although it is possible to do a great many depth dose measurements, we cannot predict how much the scattered γ-rays will contribute.

The cost of the plant is a matter on which I cannot be precise, because we have built about a plant and a half for £100 000. Moreover, it is not designed specifically for one product, but is an experimental machine. It embodies two systems with wide speed ratios, so that the cost does not bear any close relation to a plant built for a single product.

[The author's reply to the above discussion will be found overleaf.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 3RD NOVEMBER, 1959.

Mr. T. S. Millen: In outlining known uses for irradiation, the author has not indicated whether there are preferential applications, as, for example, in the initiation of chemical reactions. It would seem easier to use a γ-ray source in those cases where the chemicals must be contained in vessels under pressure or vacuum.

With regard to the commercial possibilities of irradiation, it must be recognized that novelty will always attract some customers, but an economic return is essentially the long-term acceptance of a process. It is encouraging that further installations are now in operation and that possible new applications are steadily being added to the list. As operating experience and confidence are built up, there is every reason to expect major progress in the next few years. Meantime, pilot work is helpful, and experimental irradiation laboratories enable techniques and processes to be checked but do not give a direct guide to ultimate costs because of the limits imposed by available power and beam utilization.

The economic benefit of greater power is evident from the American data quoted in Table 3. It is interesting that the size of installation selected by the author for costing in Section 7 is comparable in power with the smaller of the two accelerators listed in Table 3 and that the two estimates of the cost of irradiation per megarad-pound are in close agreement.

On the question of beam utilization, it is inevitable, in a multi-purpose laboratory, that most treatments are handled at less than the maximum efficiency. The conflicting requirements of radiation screening and catering for all shapes and sizes of subject are the essential difficulties. It is obvious from the paper itself and from the contributions to the discussion that considerable mechanical ingenuity is needed to ensure maximum utilization of the available beam, and this is perhaps the key to the immediate extension of the process.

Mr. G. V. Sadler: Could the author state whether partial polymerization of a specified extruded p.v.c. section could be achieved by irradiation, in order to reduce the flexibility of one half of an extruded tube, and retain the initial flexibility of the other half, which is slotted? Furthermore, is it practicable to stiffen a length of extruded channel section by the insertion of fillets, with a layer of styrene between the fillet and the channel section, by irradiation? This would enable small quantities of special-section plastic material to be made without the expense of tooling up for quantities by the usual injection-moulding methods.

It is apparent that the movement of materials for irradiation

* ANDERSON, L. C., *et al.*: *Industrial Engineering Chemistry*, 1957, **49**, p. 1891.

† BALLANTINE, D. S.: *Modern Plastics*, November, 1954, **32**, p. 131.

* OVADIA, J., HEINMETS, F., and HERSCHMAN, A.: 'Radioactivity Induced during Sterilization with 25 MeV Electrons', *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy*, 1958, **27**, Part II, p. 418.

into, and out of, the irradiation chamber presents new problems in materials handling, and the conveyor systems illustrated in the paper would seem to be unduly expensive to manufacture, in view of the special materials used and special conditions to be met. I suggest that, in the case of Fig. 12 where a series of boxes have to be irradiated, the conveyor system be replaced by a concrete channel filled with water, and the boxes be mounted on aluminium pontoons which could be floated through the chamber at any desired speed. The water itself would be useful as a seal in the labyrinth, and could be readily changed as required.

Alternatively, for some objects, a stainless-steel endless wire rope, passing through the chamber from top to bottom, could form the means of attachment for the objects, and would simplify the labyrinth.

In Table 4, how many hours per week is envisaged for 'continuous service'? It would appear that running costs should be somewhat below £2, which is the figure given for hourly running costs on a 40-hour-week basis.

Mr. D. D. Mold: The laboratory which my company operates is a compact self-contained unit housing a horizontally mounted 4 MeV linear accelerator, with the associated control and material conveying equipment.

The electron beam passes from the accelerator along a tube projecting through the wall which divides the accelerator room from the treatment room. It is scanned electromagnetically to produce at the 0·005 in aluminium window a rectangular beam $\frac{1}{2}$ in wide and adjustable in length up to 10–11 in.

The treatment room contains a general-purpose moving table for holding experimental specimens and a conveyor for larger quantities of material.

The work so far has been mainly on an experimental scale. Of major importance is the sterilization of such things as surgical sutures, knives and dressings and of pharmaceuticals. Among the plastics irradiated to produce cross-linking, polyethylene bulks largest; sheet, tubing, finished mouldings and insulation on cables are some of the forms it takes. Polypropylene, polystyrene and p.v.c. have also been treated.

Another successful application of the linear accelerator is in the life testing of materials. An example worth noting is the treatment of oils and greases to thousands of megarads in a matter of hours, as against weeks of treatment required with, say, cobalt 60. In only a few hours, an O-ring seal which was subject to repeated pressurization and evacuation was irradiated and tested, the dose being the equivalent of 12 months' reactor life.

Special arrangements are sometimes needed; for example, forced cooling of specimens, temperature measurement during treatment and irradiation in atmospheres other than air.

The electron beam has been used to provide X-rays for radiographic work. The high X-ray energy and intensity make it possible to obtain radiographs of metals with quite short exposure times.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. M. C. Crowley-Milling (*in reply*): I am interested to learn from Mr. Jefferson that the price of cobalt 60 is now equivalent to £20 000 per kilowatt, or 6s. 8d. per curie, compared with the published price of £2 per curie. The claim that this is comparable in price with radiation from machines does not take into account the efficiency of utilization, which may be less than half that which can be achieved with electrons. In addition, claims have recently been made that new developments may reduce the cost of electron power considerably.* I thank him for the description of the experimental irradiation plant, and for further details of the Australian plant for goat-hair sterilization. I hope that the cost figures for the latter will be published. This is the first industrial γ-ray installation, and since many guesses have been made about the cost of such plants, some facts would be welcome. From his further remarks, I assume that he has now dismissed the fuel-element pond from consideration for industrial irradiation.

The question of induced activity has been raised by several speakers. The threshold energy at which a reaction can occur is of importance, but so is the relevant cross-section. Only a small proportion of the incident electron power is converted to high-energy X-ray quanta. The cross-section for photo-neutron production from deuterium, and the other elements mentioned by Mr. Jefferson, is small. The cross-section for activation of other materials by these neutrons is also small. Thus even the most pessimistic calculations, such as those quoted by Mr. Saxon, show that negligible activity will be caused by electrons up to 18 MeV, and materials irradiated at higher energy should be safe after a short storage period. The staff of the Quartermaster's Division of the U.S. Army has estimated that the extra radiation received through an annual consumption of one ton of food which had been irradiated with 24 MeV electrons before storage would be less than the difference between the natural radiation level in Chicago and Denver, or that in a stone house and a timber one.

* 'Radiation Costs to Dip', *Chemical and Engineering News*, October, 1959, p. 48.

I thank Mr. Manley for his information about the polysulphones. With regard to smaller machines, I have published a curve* which shows that the cost per kilowatt increases rapidly as the size of machine decreases, especially for high energies.

Mr. Sadler's ingenious proposal for the formation of special sections is possible, but likely to be too expensive for practical use. The polymerization of p.v.c. by radiation may need special additives. The proposals for simplified conveyor systems merit consideration, but they have obvious limitations. In Table 4, the continuous service is based on an average of 148 hours per week, allowing a generous time for maintenance.

I agree with Mr. Millen that the utilization efficiency may be the determining factor in whether a process is economically feasible, and that there is a place for both electrons and γ-rays in the future of industrial irradiation, but I think that electrons will play the major role. It is perhaps ironical that the organizations formed to investigate the use of radioactive isotopes for irradiation, in the hope of assisting in the disposal of waste fission products, are turning to cobalt 60, which is not a fission product, for most of their proposals. There are even suggestions in the United States of building special reactors for the production of cobalt 60, and thus adding to the waste-product disposal problem.

* 'The Economics of Machine Sources of Radiation', *International Journal of Applied Radiation and Isotopes*, 1959, 6, p. 207.

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SUBMERSIBLE PUMPING PLANT

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SUMMARY

Submersible pumping units have been developed to a sufficiently high degree of reliability and efficiency to capture a large part of the field previously held by the conventional borehole pump with surface motor. The paper commences with a description of the submersible pump and the submersible motor as separate units, together with sectional drawings, constructional details and performance characteristics.

An investigation is made of the efficiency, testing and behaviour of the pump and motor under abnormal and transient conditions of starting, zero-head operation and reverse rotation, details being given of the energy dissipation and the turbine phases of the pump and of the runaway speeds attained in the reverse rotation. The question of optimum diameter of the pump set and borehole for water-supply installations is examined from the economic aspect, and the implications of corrosive waters are studied.

Problems arising from the linkage of the pump to the motor include the radial and axial loadings from pump to motor thrust bearings, the effect of these loadings in producing upthrust and downthrust and the motor starting-torque investigations.

LIST OF SYMBOLS

Hydraulic.

Q = Pump flow, g.p.m.
τ = Mechanical time-constant of the kinetic energy of the rotor, sec.
w = Total weight of pump and motor rotors, lb.
k = Mean radius of gyration of pump and motor rotors, ft.
N = Angular velocity of the rotor, r.p.m.
P_m = Horse-power of motor.
l = Length of pipeline, ft.
v = Velocity of flow in pipeline, ft/s.
μ = Friction coefficient for smooth pipe flow.
g = Acceleration due to gravity, ft/s^2.
h = Total operating head on pump.
h_s = Static head.
h_r = Mean retarding head on pipeline column.
x = wk^2 reference co-ordinate.

Electrical.

u = Tangential velocity of rotor.
t = Radial clearance or air-gap between stator and rotor.
ν = Kinematic viscosity.
r = Mean radius of stator and rotor.
m = Numerical constant.
C = Numerical coefficient.
L = Length of stator or rotor.
P = Power loss due to friction in air-gap.

(1) INTRODUCTION

Centrifugal pumps have been used for borehole and deep-well duties since about 1900, when they replaced reciprocating units. Initially, the pumps, situated at the water level, were driven by vertical-spindle electric motors at ground level, the pump being suspended from its motor stool by rising main pipes and driving shaft. Considerations of cost, maintenance and efficiency, however, led to investigation and development of submersible motors below the water surface attached directly to the pumps. Over the last twenty or thirty years, submersible pump sets have found increasing applications, so that they are now as much in use as the shaft-driven type.

The paper describes a submersible pumping plant, in particular that of one British manufacturer. A typical pumping set comprises a vertical multi-stage centrifugal pump and a squirrel-cage electric motor running in liquid, generally water or oil. The original centrifugal borehole pump, with the motor at the surface, involved the provision of intermediate vertical shafting, bearings, piping, lubrication system, etc., and associated headgear, which were expensive and which imposed a limit on rotational speed.

The submersible pump set, by avoiding this shafting, can run at a higher speed, thereby effecting considerable saving in cost. On the balance of efficiency between the shaft-driven borehole and the submersible pump set, little advantage accrues either way on medium duties. The motor of the shaft-driven set running in air suffers no efficiency loss, but frictional power losses are incurred in the vertical shafting and in the thrust bearing supporting this shafting. Since the submersible-motor rotor runs in water, power losses arise due to the friction and eddies of the water, and, in addition, electrical-resistance losses are involved in the vertical cable from the surface to the motor.

Each type, therefore, suffers losses over and above those found in a normal horizontal pumping application, the incidence of which determines the relative advantage. In practice, small-quantity high-head duties where high speed is an advantage favour the submersible pumping plant, but the large-quantity lower-head duties appear to be more satisfactorily met by vertical shaft-driven pumps, and, in consequence, slow-speed large-power submersible motors (e.g. over 500 h.p.) are not yet in common use.

The application of the submersible unit to borehole duties, where high rotational speed permits a smaller and cheaper borehole, has resulted in submersible plant developing along the lines of relatively small-diameter long units on a vertical axis. At present, probably more submersible pumping sets are being manufactured than surface-motor shaft-driven pumps, the most common applications being for waterworks and mine-drainage duties.

(2) GENERAL DESCRIPTION OF THE PUMP SET

A sectional drawing of a submersible pump of low specific speed is shown in Fig. 1, whilst a motor and a pump of medium specific speed is shown in Fig. 2. Specific speed is a type ratio describing, in terms of duty and speed, the shape of the flow passage of the impeller and the chamber. The efficiency of the pump is primarily determined by its specific speed and its output (see Section 17). The pump is placed above the motor, the water inlet being between the units, which arrangement keeps down the overall diameter of the set, since the discharge water

Mr. Anderson and Mr. Crawford are with the Harland Engineering Co. Ltd., Alloa.

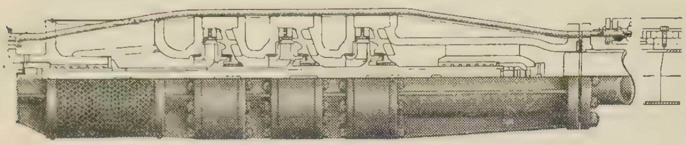

Fig. 1.—Low-specific-speed submersible pump.

area and gives the characteristics shown by broken lines in Fig. 3. Here, the head characteristics fall steeply as flow is increased; the horse-power characteristic is flat and non-overloading at the best efficiency point. This means that a motor provided to meet the best efficiency duty will not be overloaded however the operating head may vary.

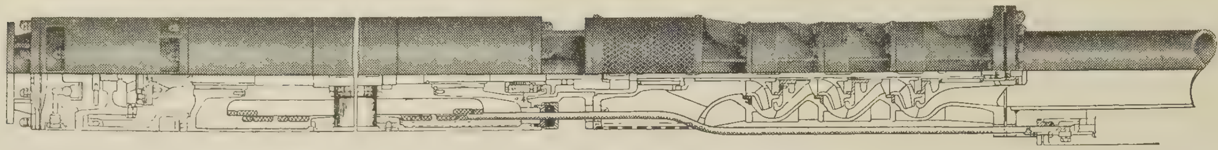

Fig. 2.—Medium-specific-speed submersible pump and submersible motor.

need not pass round the motor, and avoids an additional pressure-wall cable gland.

The pump stages, three of which are shown in Fig. 1, are clamped between a delivery cover at the top and a suction cover, which is attached to the motor and contains the inlet strainer. Each stage comprises a chamber, an impeller and renewable wearing bushings at the impeller neck and hub, the impeller being clamped on the shaft by sleeves and nuts which protect the shaft against corrosion. A neck ring may be fitted to each side of the impeller and balance holes drilled through the driving shroud so as to effect hydraulic balance as far as the generated pressure is concerned. The suction and delivery end covers carry the bearings for the shaft, but, in addition, some measure of shaft support is afforded by the stage bushings. A rotating umbrella is fitted to the lower pump bearing to prevent the access of dirt, grit, etc., to the bearing surfaces, whilst the upper journal bearing is blind at the top and may embody a small thrust pad to limit any shaft uplift at the minimum heads described below.

The power of the motor is transmitted to the pump via a claw coupling, which permits the shafts to float freely with respect to expansion and allows the pump shaft to rise under uplift conditions independently of the motor shaft. The downward thrust of the pump shaft is normally carried by the motor thrust bearing, although where the water is non-abrasive a hydraulic balancing disc may carry the pump thrust independently.

(2.1) Materials of Construction

The pump materials are very largely dictated by the quality of the water being handled, but, in general, the pump covers and chambers are made of cast iron or bronze and the impellers and wearing bushings of bronze. The shaft is normally of stainless steel or high tensile steel and carries stainless-steel nuts and sleeves running as journals in water-lubricated guide bearings of carbon, plastic or rubber. The uplift thrust bearing on the top of the pump and the umbrella to the lower bearing are made of bronze.

Where a bronze pump is fitted to a mild-steel motor and a mild-steel rising main, discs of Bakelized fabric are fitted between the flanges to provide insulation against electrolytic potential.

(3) PUMP PERFORMANCE CHARACTERISTICS

The head, quantity, power and efficiency characteristics of low- and medium-specific-speed submersible pumps are given in Fig. 3. Determination of dimensions for a given duty is given in Reference 1.

(3.1) Medium Specific Speed

The pump illustrated in Fig. 2 (medium-specific-speed type) has relatively small-diameter impellers with respect to the flow

(3.2) Low-Specific-Speed Pump

The full lines in Fig. 3 show the performance of the larger pump of low specific speed where the head characteristic is flatter but the horse-power curve rises as quantity is increased.

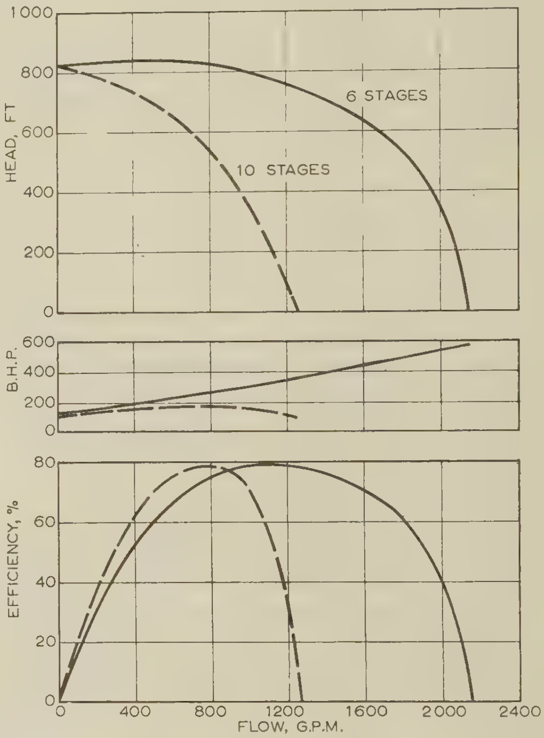

Fig. 3.—Pump characteristics of quantity, head, efficiency and power.
—— Low specific speed. ---- Medium specific speed.

With a pump of this type it is essential to ensure that adequate motor power is provided for any possible head variation on site.

In consequence of the low specific speed, a smaller relative area is provided to the casing guide ports and a higher flow speed results. To protect against erosion, therefore, the low-specific-speed pumps are fitted with renewable bronze guide ports in the chambers, illustrated in Fig. 1. Such renewable guide ports are, however, unnecessary on the medium-specific-speed pump and are omitted in Fig. 2.

When required to operate continuously down to low heads, the low-specific-speed type can be designed to give characteristics similar to the broken lines of Fig. 3 in order to avoid the pro-

vision of a relatively large motor. The cost is increased by the need to provide extra stages and the efficiency is slightly reduced.

(4) TEST PROCEDURE

Submersible pump casings are hydrostatically tested, generally to 1·5 times the maximum working pressure. The pump set is then run at normal speed in order to determine the characteristics of quantity, head, power and efficiency, and to ensure that all guarantees are satisfactorily met. This is carried out in accordance with the British Standard Pump Test Codes, B.S. 599 and B.S. 722.

(5) STARTING CHARACTERISTICS

The starting torque required by a submersible pump is shown in Fig. 4. At zero speed, the static friction torque must be

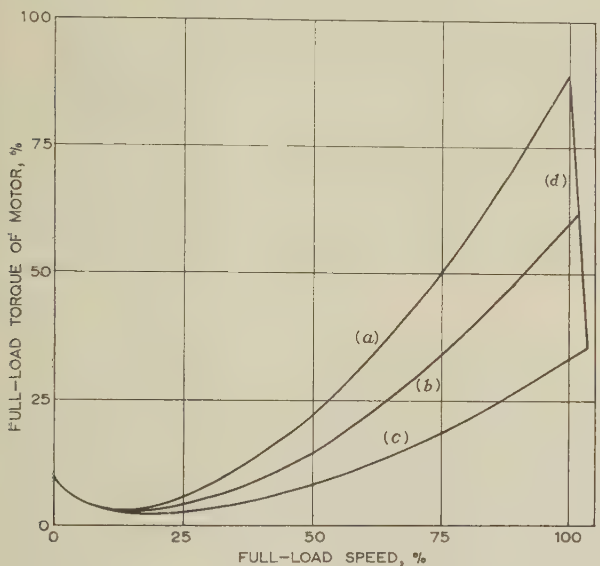

Fig. 4.—Starting torque of submersible pumps.

(a) Started with valve open. Static conditions permitting flow of water immediately.
(b) Medium-specific-speed pump. } Started with valve closed. High static lift preventing flow of water until full speed is approached.
(c) Low-specific-speed pump.
(d) Valve opening.

overcome, for which a safe allowance of 10% of full-load torque is made, since there is no gland friction. The torque taken by the pump then falls to meet the line of torque proportional to speed squared. For a zero-head start, the upper curve is used, corresponding to immediate flow. When started against full head or closed valve, the pump approaches full speed before flow can start, and the starting torque follows curve (b), medium specific speed, or curve (c), low specific speed.

(6) OMISSION OF FOOT VALVE

In order to avoid pressure surges and risk of sticking, the foot valve may be omitted, permitting the pump to reverse when power is switched off or fails. This involves a start against zero head, which explains the need for consideration of zero-head power consumption and thrust loading. However, the short time taken to fill the vertical column may permit operation, on a normal cold start, at slight overload of the motor. Care must be taken in cases where the water stands very high in the well or shaft under certain rainfall conditions, thus demanding fairly continuous operation at low pumping heads.

(7) OPERATING CYCLE

(7.1) Transient Conditions

The operating cycle of a submersible pump set is generally as follows:

With the well water standing at normal level and with the pump immersed in water, the motor is started. The head at the start is zero if no foot valve is fitted. As the set accelerates, the water rises in the delivery column, imposing a head on the pump. During the first minute or so, the pump operates against a head which is less than normal. On a characteristic such as the full line of Fig. 3, this may impose more than normal load on the motor, although, as mentioned above, this is usually acceptable on short-term rating.

The performance of the motor during the filling of the column is described in Section 13.

After the delivery column is filled, the pump operates at normal duty. When the set is shut down by switching off the motor or by power failure, the water column and the rotor decelerate, stop and then reverse.

The energy in the vertical water column is many times greater than the kinetic energy in the rotor (see Section 17.2) so that overspeed in reverse is reached.

The period of reversal is, however, relatively short (provided that check valves are installed on surface mains and reservoirs) before the vertical water column and the rotor finally come to rest at zero head.

(7.2) Abnormal Conditions

The complete characteristics of a centrifugal pump are shown in Fig. 5 to illustrate the pump behaviour on power failure. Here the pump performance is plotted when running as a normal

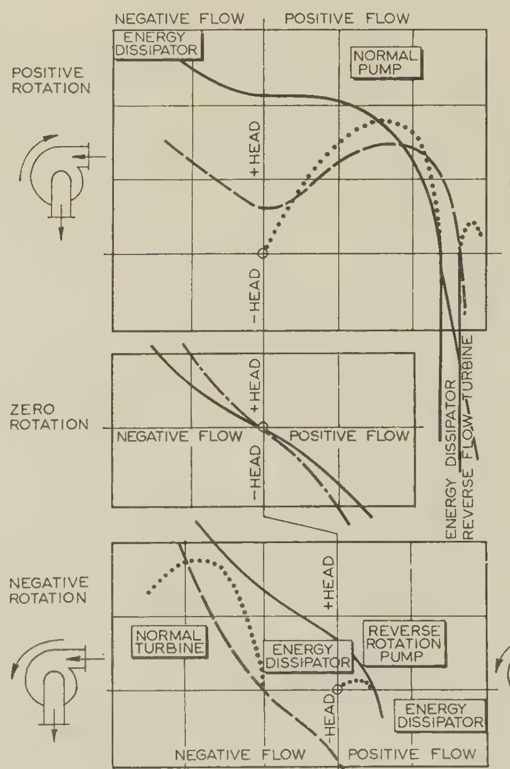

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Fig. 5.—Complete characteristics of centrifugal pump.
—— Head. ······ Efficiency. ---- B.H.P. —·— Torque.

pump and as a reverse-flow turbine at zero speed, and when running in reverse as a normal turbine and as a reverse-flow pump. Between pairs of these phases, zones of energy dissipation occur.

Submersible units have relatively small rotational inertias. For example, a typical set may have a kinetic energy in its rotor equivalent to the energy necessary to drive it at full speed and full load for only $\frac{1}{3}$ sec (i.e. the mechanical time-constant is $\frac{1}{3}$ sec).

The low mechanical time-constant results in the column being master of the rotor, and therefore the sequence on power failure (see Fig. 5) is as follows:

Normal pump.
Energy dissipator.
Reverse-flow turbine.
Energy dissipator.
Zero rotation.
Normal turbine.
Turbine at runaway speed.
Slow down to stop at zero head.

The important stage here is the runaway speed in reverse, generally about -120% of the normal speed. It is essential that the rotor shall safely withstand this speed and that the thrust bearing shall permit reverse running.

Fig. 18 illustrates the balance of inertias of rotors and water column and assists in the solution of pipeline problems after power failure.

(8) JOURNAL AND THRUST-BEARING LOADINGS

(8.1) Radial Loads

The pump impeller discharges into several guide ports uniformly spaced around the circumference so that radial unbalance is slight and is easily handled by the journal bearings.

(8.2) Axial Loads

The pump axial load may be taken on a balance disc or may be carried via the coupling on to the motor Michell bearing. Since a water-lubricated thrust bearing can handle only a load in the neighbourhood of one-quarter that of a similar oil-lubricated bearing, the axial loading of the pump when carried by the motor thrust bearing must be considered in the overall design study. In order to reduce thrust, each impeller is hydraulically balanced by having a neck ring at the upper side in addition to one at the lower (inlet) side. Holes through the impeller driving shroud then return the back neckring leakage water to the low-pressure side of the impeller, thereby effecting balance. The top end of the pump shaft, however, is usually subject to delivery pressure, whilst the lower end is subject to inlet pressure: this produces a vertical downward thrust proportional to the generated head.

Each impeller turns the water flow through approximately 90°, which gives rise, according to Newton's second law, to a dynamic upward thrust proportional to the square of the flow. The motor and pump rotors impose downthrusts equal to their respective weights. The summation of these thrusts is shown in Fig. 6, where thrust in pounds is plotted against percentage flow.

At zero flow the weights of the pump and motor rotors and the downthrust due to differential pressure on the pump shaft end are carried by the motor thrust bearing. As the flow increases there is a dynamic upthrust proportional to the square of the flow, which ultimately exceeds the decreasing pressure thrust as zero generated head is approached. The dynamic thrust at large flows produces an upthrust on the pump shaft which is held by a small thrust bearing at the top of the pump. This removes some load from the motor thrust bearing, which, however, must always carry at least the motor rotor weight, since the coupling faces are free to slide apart for a short distance.

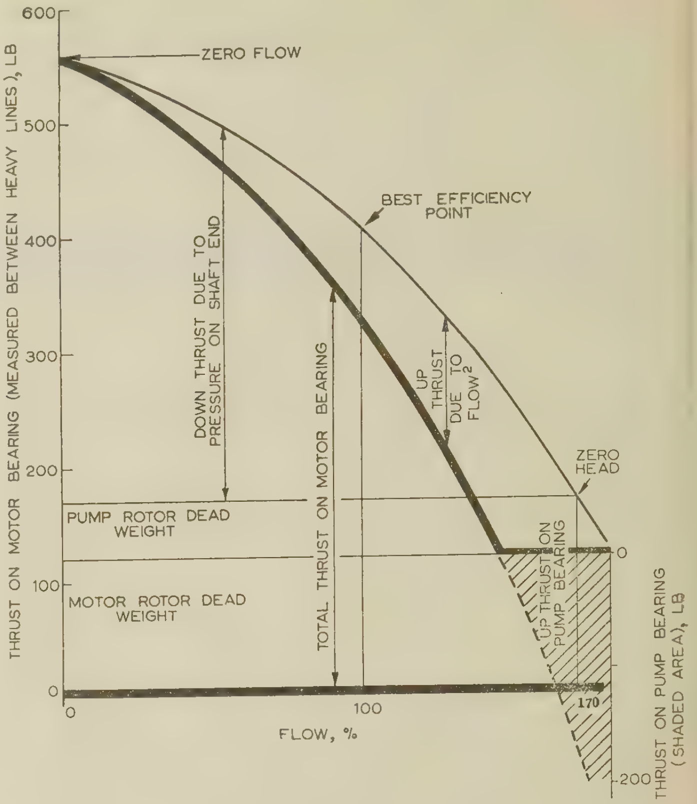

Fig. 6.—Axial thrust loadings on submersible pump set.

Fig. 6 shows the downthrust on the motor bearing as the vertical distance between the heavy lines, the dynamic upthrust being measured as a reduction of the pressure thrust. The pump upthrust is shown as a vertical height of the shaded area where the dynamic thrust line is below the pump-rotor weight line for the flow in question. The motor thrust bearing is of the Michell type, water-lubricated, and is continuously rated for maximum load. The pump uplift bearing is a small bronze pad against which a bronze cap on the shaft can run during uplift conditions. This bearing is generally short-term rated at zero head, but is continuously rated at half normal head.

At unattended or automatic stations where the water level in the well may be high at start up, the uplift bearing has an important duty to fulfil, since, dependent upon the well characteristics, uplift thrust may persist for a considerable time until normal well level is reached.

(9) ECONOMIC CONSIDERATION OF DIAMETER OF BOREHOLE AND TYPE OF PUMP

A submersible pump is essentially multi-stage, and advantage is taken of the vertical operation to reduce the casing diameter and increase the overall length without prejudice to mechanical stability. Beyond a certain point, however, this reduction of diameter is a prejudice to efficiency, and consequently this aspect must be investigated with respect to the cost of the borehole. Some slight efficiency reduction has occasionally been justified where a large yield is required from a relatively small borehole or where the boring cost is high.

In the overall economic study of any scheme, the additional cost of a larger borehole must be balanced against the capitalized saving in efficiency.

When considering the relative merits of a normal borehole-pump/surface-motor installation and of a submersible pumpset, many of the above factors have to be taken into consideration. Normally, there is a substantial reduction in the capital cost when a submersible unit is installed. In many instances it is unnecessary to build a pump house, by operating instead in open air. A pump house may, however, be required for other reasons, such as housing booster pumps, measuring equipment, control gear, etc., but it can frequently be made smaller and therefore cheaper.

The effect of depth must also be considered, since sacrifice of efficiency is involved where a high head per stage with a small quantity is required.

(10) GENERAL DESCRIPTION OF MOTOR

Fig. 2 is a sectional drawing of a typical submersible pumpset with a wet-type motor. The motor stampings are mounted in a mild-steel tube and those of the rotor directly on a stainless-steel shaft. The motor, which normally runs with its shaft vertical, has two guide bearings and a thrust bearing. As the bearings are of necessity water-lubricated, the bearing design, though based on normal principles, is unconventional in some aspects, such as the choice of materials. To prevent the entry of grit and contaminated water, a carbon shaft seal is fitted at the driving end. This seal is effective only if the pressure difference between the internal and external water is small. To ensure that this is so, an expansion chamber with a rubber diaphragm is fitted at the bottom of the motor. The stator has a simple pull-through winding in tunnel slots.

(10.1) Motor Guide and Thrust Bearings

Since the motor normally runs with its shaft vertical, the guide bearings are lightly loaded, and a plain carbon bush running on an easily renewable stainless-steel sleeve on the motor shaft has proved very satisfactory in practice. The guide bearings are carried in cast-iron housings tucked right inside the stator end windings. Alternating e.m.f.'s will therefore be induced in the bearing housings by the leakage field of the stator end windings. These e.m.f.'s may cause currents to circulate between the bearing bush and the bearing journal. That these currents are harmless is shown by the satisfactory performance of large numbers of motors fitted with this type of bearing. This is to be expected, since carbon is so successfully used for taking currents in and out of slip rings and commutators. A change to more conventional bearing materials could, however, quite easily result in serious difficulties.

In contrast to the guide bearing, the thrust bearing is heavily loaded, since it has to carry the weight of the rotor and the downward hydraulic thrust from the pump, as shown in Fig. 6. The bearing diameter is limited by the motor diameter, and the pressure is therefore high for a water-lubricated bearing. Nevertheless, several satisfactory designs have been evolved. One of the earlier designs had carbon pads running on a stainless-steel thrust plate. As the surface of the pad was rather rough and never acquired a high polish in service, it is unlikely that true hydrodynamic film lubrication was obtained in these bearings. The operating conditions probably approximated to boundary lubrication. A large number of motors with this type of bearing are in service, and operating experience has shown that they all give many thousands of hours of trouble-free service with little or no observable wear on the carbon pads.

More recent experience has shown that a change from carbon to white-metal tilting pads is accompanied by a reduction in the measured 'windage and friction' losses in the motor. This naturally results in an improvement in motor efficiency and shows that better bearing performance is being obtained.

(10.2) Control of Corrosion inside Motor

In spite of the carbon seal and expansion chamber, it does not appear to be possible to prevent the gradual contamination of the water inside the motor by the well or mine water, and so it is necessary to take steps to eliminate or control the corrosion.

As already mentioned, the motor shaft is made of stainless steel. The grade of stainless steel chosen should have reasonable magnetic properties, since the shaft must carry some of the working flux, particularly in two-pole motors.

The stator and rotor core iron are the parts most liable to corrosion, but experience has shown that serious corrosion is normally confined almost entirely to a short length at each end of the core. This corrosion can be effectively controlled by making about two inches at each end of the rotor core of stainless steel having reasonable magnetic properties. To reduce the corrosion of the stator core, about $\frac{1}{4}$ in of the same grade of steel plate is used at each end. For the remaining active iron of the machine, the normal core-plate insulating varnish offers good protection against corrosion. These precautions provide adequate protection against corrosion in most cases. There are several instances of motors being in service for 50 000 hours or more without lifting for examination or maintenance.

Where the water is unusually aggressive, it may be necessary to provide a flow of clean fresh water to the interior of the motor. At the same time, the outside of the motor may also require special protection.

(10.3) Motor Stator Winding

The successful operation of the wet-type submersible motor is entirely dependent on the availability of insulating materials which will maintain a high insulation resistance during many thousands of hours of operation under water. Of the several materials which are available and have been tried, polyvinyl chloride (p.v.c.) has been found to be the most satisfactory. As p.v.c. is virtually unaffected by long immersion in water, it is ideal in this respect. Since its physical properties are, however, rather unusual, due allowances must be made in the design and construction of wet-type submersible motors. P.V.C. is extremely tough and resistant to abrasion but will deform more or less continuously when subject to long sustained mechanical pressure at any one place. Under these conditions, the p.v.c. insulation on the winding wire would flow away continuously until the insulation became so thin that breakdown occurred. The stator winding must therefore be so designed and constructed that the wire covering is not subject to long sustained mechanical pressure. This condition is easily fulfilled in the slots as it is necessary only to leave the winding slack enough to avoid undue mechanical pressure.

The stator winding is a three-phase pull-through concentric winding, each phase being wound with a single length of p.v.c.-covered wire. The slot liner is a thin sheet of Alkathene.

As the p.v.c.-covered winding wire must be very flexible for a pull-through winding, the winding outhang is not very strong and must be adequately braced to prevent its collapsing under the action of electromagnetic forces at starting or hydraulic forces during normal running. The rigidity of the winding outhang can be greatly increased if the conductors are taped together. The tape used for this purpose must not be capable of applying undue mechanical pressure to the wire covering, nor must it rot and decay during the life of the motor. P.V.C. tape is obviously the ideal material for this purpose and fortunately is readily available. If a thin tape is used, sufficient solidity can be imparted to the winding outhang to prevent collapse under normal operating conditions. At the same time, excessive

pressure cannot be applied to the wire covering because if the p.v.c. tape is pulled too tight it will stretch and release the pressure. In spite of all the precautions that are taken, slight deformation of the wire covering is bound to occur and must be allowed for when fixing the nominal thickness. The wire covering used is much thicker than is normal in low-voltage machines, and consequently the space factor in the slot is low and is made lower still by the need to keep the winding slack in the slot. This greatly increases the difficulty of getting the desired outputs from small-diameter machines.

One of the main objects in using the pull-through stator windings is to reduce the number of joints to a minimum, as all joints are a possible source of weakness in a wet-type machine. Since each phase is wound with a single length of wire, only four joints are necessary in a star-connected machine, namely the star-point joint and the joints between the winding wire and the outgoing cable. All are insulated with a special adhesive insulating tape, which is quite unaffected by long immersion in water or water-solvac solution. The essential features of a satisfactory joint-insulating technique are care and cleanliness.

Once the stator is completely wound, it is immersed in water for a week and the insulation resistance checked daily. On the satisfactory completion of this immersion test, the winding is flashed at 1·5 kV while still in water and the stator is then passed to the fitting shop for assembly. The stator winding of a high-voltage submersible motor is very similar to that of a low-voltage one, except that the insulation thickness has to be increased to make it suitable for continuous operation at 3·3 kV with a very generous allowance for the effects of possible flow of the p.v.c. insulation from any points subject to mechanical pressure. In mining applications where there is usually no restriction on the motor diameter, the number of joints actually in contact with the water can be reduced to one, the star-point joint, by taking the three free ends of the winding wire straight into a sealing chamber mounted on the motor. The joints are taped with the same grade of adhesive waterproof tape as is used in the low-voltage machines. The sealing chamber is then filled with a waterproof sealing compound to prevent the water from coming into contact with the joint. The star-point joint is thus the only joint in direct contact with water and is at or near earth potential, so that the risk of breakdown there is probably no greater than in a low-voltage motor.

(10.4) Motor-Rotor Winding

The rotor winding is a conventional squirrel-cage rotor winding with uninsulated bars. The bars are normally rectangular in section, but in the larger four-pole motors inverted-T-shaped bars are normally used. The bars are brazed into slots milled in copper short-circuiting rings at each end of the core. After the brazing operation, the short-circuiting rings are machined to a smooth surface.

(11) MOTOR DESIGN

The design of the wet-type submersible motor is, of course, based on the conventional theory of the induction motor, but there are several unusual features which deserve detailed attention.

To keep the friction losses due to the water in the air-gap to a minimum, tunnel slots are used on both stator and rotor. The motor has, therefore, an inherently high reactance.

As a large part of the leakage reactance is due to flux in the magnetic bridges across the stator and rotor slots, it is very dependent on the current flowing in the machine windings. These effects are quite pronounced at currents well below the normal full-load current. It follows, therefore, that the effective reluctance of these leakage flux paths varies greatly throughout a single cycle of motor current, and the conventional circle diagram cannot give a true representation of the motor performance. In general, it is found that, if a test circle diagram is drawn using the reactance as determined from a locked rotor test with full-load current in the stator winding, the full-load power factor as determined from the test circle diagram is higher than that actually measured with the motor running on full load.

As the air-gaps in induction motors are small, the shafts must be very stiff. The usual practice in conventional machines is to make the shaft stiff enough to ensure that the deflection is less than 10% of the air-gap length when the motor is lying with its shaft horizontal. Submersible motors are very long and the shaft is relatively thin and flexible, and consequently the deflection in the horizontal position is much greater than in a fan-ventilated motor. A large air-gap is therefore desirable to ensure that the shaft deflection is not too large a fraction of the air-gap length. In practice, the submersible motor air-gap is about twice that of the conventional induction motor with the same rotor diameter.

Tests have shown that a submersible motor with water in the air-gap can run at its calculated critical speed without a noticeable increase in vibration. Consequently, submersible motors can be run either below or above their critical speed as may be convenient. A group of machines on a given frame diameter is normally designed so that the machines with the shorter core lengths run below their critical speed, and those with the longer core lengths run above their critical speed. No machines are designed to run at their critical speeds, although this would be quite safe.

As the rotor shafts are long and thin they are extremely flexible. Direct measurements show that the shaft deflection is much less than calculated if the calculation is based on the shaft stiffness only. This increase in rigidity can be due only to the stiffening effect of the rotor stampings and bars. Good agreement between the calculated and observed deflections can be obtained by calculating the second moment of area of the shaft and rotor bars separately and adding them to find the total second moment of the assembly. The combination of high leakage reactance and large air-gaps means that submersible motors are inherently low-power-factor machines. Numerous attempts to design these machines in such a way as to improve the power factor have shown quite clearly that it can be improved only at the expense of some other aspect of machine performance. The best procedure, therefore, is to design the machine ignoring power factor altogether and then, if necessary, to use a capacitor to correct the power factor.

(11.1) Motor Losses due to Water in Air-gaps

When a submersible motor is running at normal speed, the water in the air-gap is in violent motion. The nature of the fluid flow under such conditions was investigated by Taylor[2] some time ago. He showed that stream-line flow such as exists in a journal bearing cannot exist in the gap between two concentric cylinders, one of which is rotating, if the Reynolds number exceeds a certain critical value. With the inner cylinder rotating, this critical Reynolds number is given approximately by

$$\left(\frac{ut}{\nu}\right)_{crit} = 41 \cdot 3\sqrt{\frac{r}{t}}$$

When the Reynolds number exceeds this critical value, the laminar flow which exists in a journal bearing breaks down and is replaced by a series of cellular vortex rings of approximately

square cross-section. Some interesting photographs published recently by Cole[3] show these square vortex rings very clearly. One of Cole's photographs is reproduced in Fig. 7. For a small

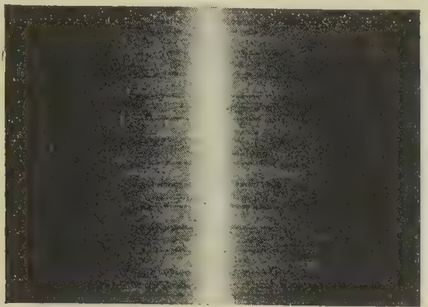

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Fig. 7.—Vortex formation in liquid between concentric cylinders with inner cylinder rotating.

range of Reynolds number, Taylor's results indicated that the loss in the air-gap is given approximately by an expression of the form

$$P = CN^{3-m}r^{4-m}t^{-m}L$$

Tests on a group of motors show that m is about 0·5.

In determining these values, the total 'windage and friction' loss of the motors was used, so that the loss calculated from this equation includes bearing as well as air-gap losses. This is convenient and has been found to be sufficiently accurate for design use when applied to a range of similar machines.

In a range of similar machines the air-gap length increases as the rotor diameter increases. This increase counteracts the rapid increase in windage and friction losses as the rotor diameter increases, so that in a range of machines the windage and friction losses are approximately proportional to the machine outputs.

(11.2) Motor Efficiency

As it is imperative that the maximum possible output be obtained from a given size of submersible motor, the core iron is operated at very high flux densities which are maintained throughout a range of similar machines. The iron losses are proportional to the volume of active iron in the stator core, and consequently are roughly proportional to the output of the motor. Since the windage and friction losses are also roughly proportional to the output of the machine, it follows that the total iron, windage and friction losses of a group of submersible motors is roughly proportional to the motor output. This conclusion is fully confirmed by numerous tests on a group of machines. In this respect, submersible motors differ somewhat from a similar group of fan-ventilated motors in which the iron windage and friction losses become a smaller percentage of the output as the output increases. The result is that the efficiency of the submersible motor does not increase quite so rapidly with size as does that of the fan-ventilated motor.

The lower curves in Fig. 8 show the full-load efficiencies of a range of two-pole submersible motors. Separate curves are drawn for each frame diameter, thus showing the effects of changes in length and diameter on the full-load efficiency. The upper curve gives the average efficiency of four-pole slip-ring induction motors. The difference is quite striking. Fig. 9 gives the same information for a range of four-pole submersible motors which are normally used for the higher outputs.

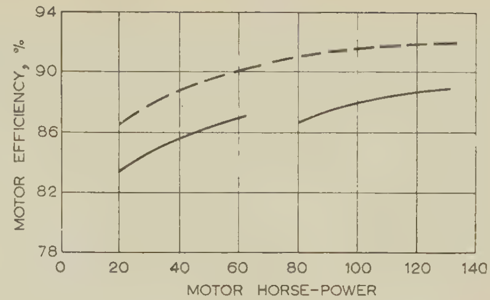

Fig. 8.—Full-load efficiency.
—— Two-pole submersible motors. ---- Four-pole slip-ring motors.

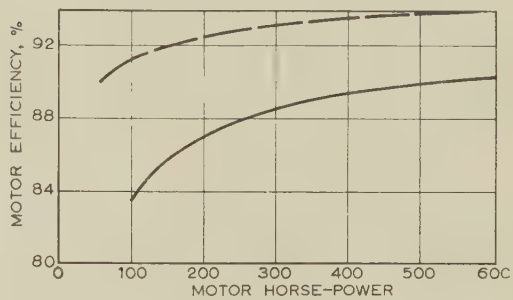

Fig. 9.—Full-load efficiency.
—— Four-pole submersible motors. ---- Four-pole slip-ring motors.

This reduction in motor efficiency is not a serious matter because it is more than compensated for by other advantages.

(11.3) Motor Temperature Rise

The wet-type submersible motor has a most efficient cooling system. This is fortunate since p.v.c.-covered wire must not be operated at temperatures exceeding 60° C if a long life is to be obtained from the motor windings. Water temperatures in this country rarely exceed 10–15° C, so that motor temperature rise of 40° C by resistance means that the total operating temperature will not exceed 50–55° C, which allows a comfortable margin for possible differences between test-bed and site conditions. Where higher temperatures do occur, the temperature rise of the motor must be reduced to ensure that the total operating temperature does not exceed 55° C.

On test, the temperature rise of the submersible motor is most conveniently determined from the change in the resistance of the stator windings. To measure the temperature rise correctly to within 1° C, when the rise is about 40° C, the hot and cold resistances must be measured with an error not exceeding 0·18%. Measurements of this degree of accuracy are surprisingly difficult when they have to be incorporated in the normal testing routine on electrical machines.

Fortunately, the Kelvin double bridge is available in commercial forms having the requisite degree of accuracy. The main difficulty in measuring the hot resistance arises because immediately the motor is disconnected from the supply its temperature falls rapidly, so that the resistance measured is not that of the machine at its running temperature but that at some lower temperature. To surmount these difficulties a Kelvin double bridge fitted with a plug switching arrangement is used, so that immediately the motor is disconnected from the line the plugs can be pushed in and the motor winding connected to the Kelvin double bridge with a delay of only a few seconds. Even so, the temperature of the windings falls appreciably and it is necessary

to take resistance readings at regular intervals so that a cooling curve, such as that shown in Fig. 10, can be plotted and extrapolated back to zero time to give the true hot resistance of the motor windings. In order that the curve can be extrapolated

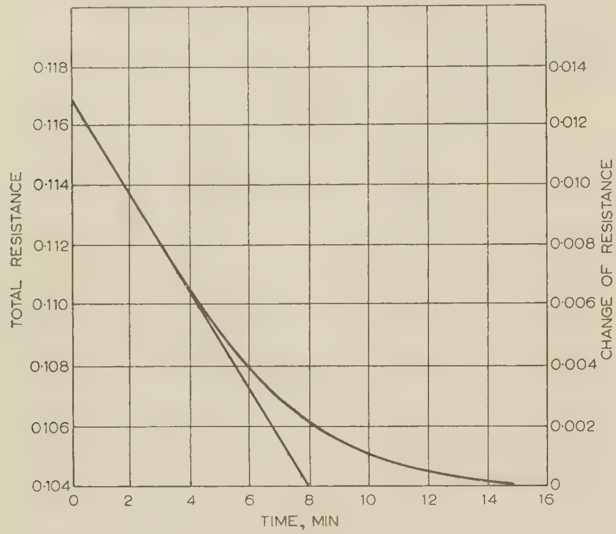

Fig. 10.—Cooling-time curve of submersible motor.

back to zero time without introducing serious errors, several readings must be taken in a time which is not greater than half the cooling time-constant of the machine.

Apart from their usefulness in determining the temperature rise, these curves are of fundamental importance in the application and operation of submersible motors. The curve in Fig. 10 is for a 70 h.p. 2900 r.p.m. motor, having, as shown, a cooling time-constant of only eight minutes. As the heating time-constant will have about the same value, the machine if overloaded will very quickly reach the steady temperature corresponding to the overload. Unfortunately, as shown in Fig. 11,

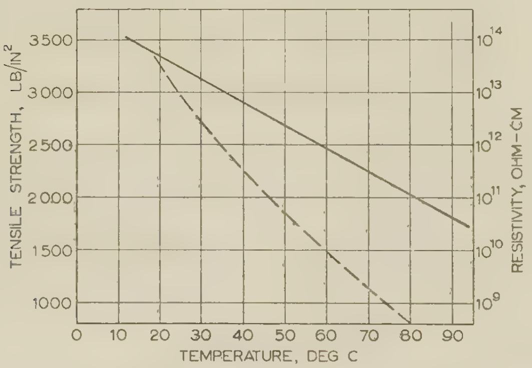

Fig. 11.—Effect of temperature on the resistivity and tensile strength of p.v.c.

—— Resistivity. ---- Tensile strength.

the mechanical strength of the p.v.c. covering on the winding wire decreases rapidly with temperature rise, so that any increase above the normal operating temperature will weaken the p.v.c. and may seriously reduce the operating life of the machine. Submersible motors must therefore be regarded as c.m.r. machines, which must be borne in mind both when selecting a machine for a particular duty and when the motor is in service.

(12) MOTOR INSULATION RESISTANCE

The resistivity of p.v.c. decreases rapidly as the temperature rises. The approximate relationship between temperature and resistivity is given in Fig. 11, where it is shown that for a temperature rise of 40° C the insulation resistance will fall to about one-hundredth of its initial value. This is confirmed by tests in which the insulation resistance of a submersible motor is measured and plotted against time as the motor cools down after works testing.

As the cooling curves of the motors are known it is easy to calculate and plot curves showing how the insulation resistance increases with time as the motor cools after shutting down. Fig. 12 is a typical family of calculated curves for a motor with

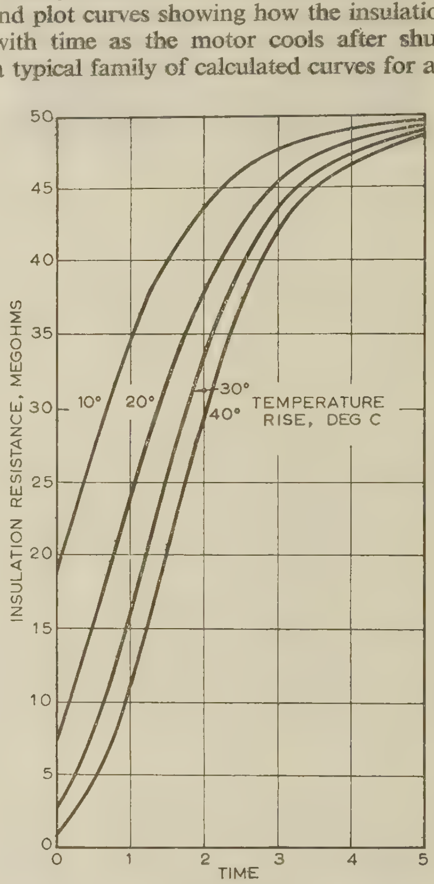

Fig. 12.—Effect of temperature rise on the insulation resistance of submersible motors.

a cold insulation resistance of 50 megohms and temperature rises varying from 10 to 40° C. The cooling time-constant is taken as unity. The shapes of these calculated curves agree very closely with those of the actual test curves.

These curves, like the cooling curves, have important practical applications. When a submersible motor is hot its insulation resistance is relatively low and it cannot, unfortunately, be improved by drying out. A low insulation resistance in a hot machine must therefore be regarded as normal and satisfactory; however, as the machine cools down the insulation resistance should increase very considerably. It is not easy to lay down a limit below which the insulation resistance should not fall. The lower limit is normally taken as 100 kilohms, and many machines are giving perfectly satisfactory service with a hot insulation resistance of only a few hundred kilohms. The real criterion is that if the insulation is sound the insulation resistance will increase substantially as the machine cools down after being taken off load. Such a low insulation resistance as this would not be acceptable in a normal fan-ventilated motor,

ut as a submersible motor is completely immersed in water t is very effectively earthed. In addition, in mining installations separate earthing lead is normally incorporated in the rising nain cable so that there is absolutely no risk of shock to personnel responsible for the operation of the plant.

(13) MOTOR STARTING CHARACTERISTICS

As submersible motors are mainly used for driving multi-stage entrifugal pumps the starting characteristics of the motors can e designed for this duty only. The starting characteristics of a 450 h.p. 1450 r.p.m. 550-volt submersible motor, shown in Fig. 13, are fairly typical of the performance of the larger

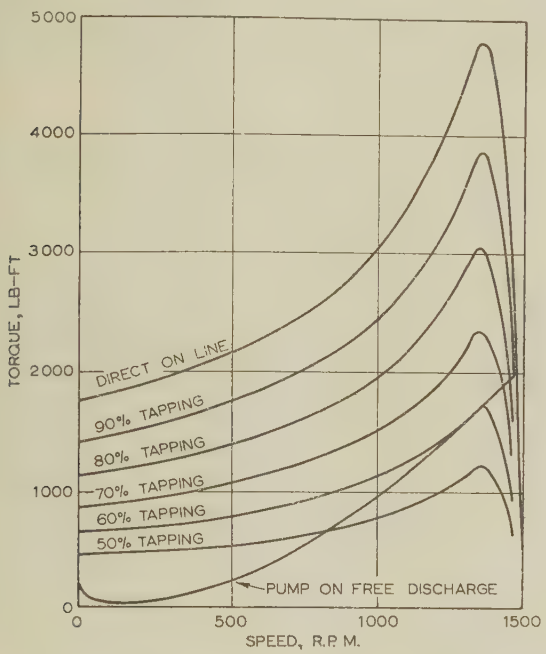

Fig. 13.—Speed/torque curves of submersible motor at different auto-transformer tappings.

submersible motors. This motor drives the pump shown in Fig. 1. Submersible motors as large as this are not normally started direct on line, because, as already pointed out, the end-winding bracing cannot be made sufficiently rigid to withstand the forces acting during direct-on-line starting. Apart from this, the power system is not usually able to supply the starting current required without a substantial drop in voltage, which may seriously inconvenience other power users on the same system. Korndorffer auto-transformer starting is therefore normal for these large motors. The auto-transformer must be at the top of the well or mine shaft so that there is a considerable length of cable between the output terminals of the auto-transformer and the motor. This cable carries the starting current of the motor, and adequate allowance must be made for the voltage drop in this cable when deciding on the auto-transformer tappings. The result is that the auto-transformer tappings for submersible motors are higher than is normal for fan-ventilated machines. Fig. 13 shows, in addition to the direct-on-line starting performance of a 450 h.p. submersible motor, the starting performance with an auto-transformer, including an allowance for voltage drop in the rising main cable but not for a fall in the supply voltage.

Under normal running conditions, the voltage drop and the losses in the rising main cable of a large low-voltage submersible motor may be considerable. This coupled with an analysis of the starting requirements frequently leads to a cable size considerably larger than would be used if the thermal rating of the cable were the only criterion.

As mentioned above, however, it is now quite common to run submersible pump sets without a foot valve so that the rising main is empty when the pump set starts up. The pump set must therefore be considered as being run up to speed on free discharge instead of on closed valve, since the speed/torque curve of a pump on free discharge is considerably higher than that of the same pump on closed valve. The difference is shown clearly in Fig. 4.

In order that the pump set may run rapidly up to its normal speed during starting, the motor speed/torque curve must be well above that of the pump. Fig. 13 shows that this condition is fulfilled if the motor is started on the 70% tapping or any higher tapping of the auto-transformer. It is worth noting that on the 60% tapping of the auto-transformer, the speed/torque curves of pump and motor touch. When this happens, there is no torque available to accelerate the pump set, which will therefore fail to run up to speed or else take an inordinately long time to do so.

If it is assumed that the running-up time of the pump set is short, the amount of water pumped into the rising main during running up will be small, and it can reasonably be assumed that the pump set is running up to speed on free discharge. With this assumption, the time taken for the pump set to run up to speed on different tappings of the auto-transformer can be calculated by conventional methods, and a curve plotted showing the running-up time on different auto-transformer tappings. The curve in Fig. 14 is typical of the results obtained. This curve is

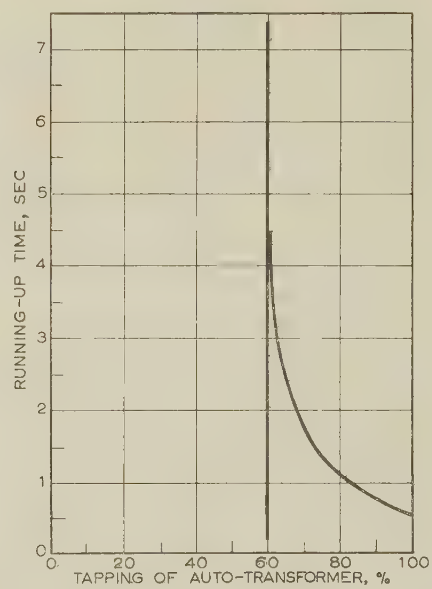

Fig. 14.—Running up of submersible motor at different auto-transformer tappings.

most interesting as it shows quite clearly that a submersible pump set must run up to speed in a very short time or it cannot be relied upon to run up at all. Having calculated this curve, the accuracy of the initial assumption can be easily checked, and is found to be fully justified.

Once the pump set is up to speed, the rising main will start to fill up with water. Fig. 3 shows that the 450 h.p. motor will be

overloaded until the pump head has risen to about 670 ft, and so it is necessary to calculate the time required to fill the rising main. To do this accurately a step-by-step calculation is necessary. The results of such a calculation are given in Fig. 15, which shows the height of the water in the rising main and the

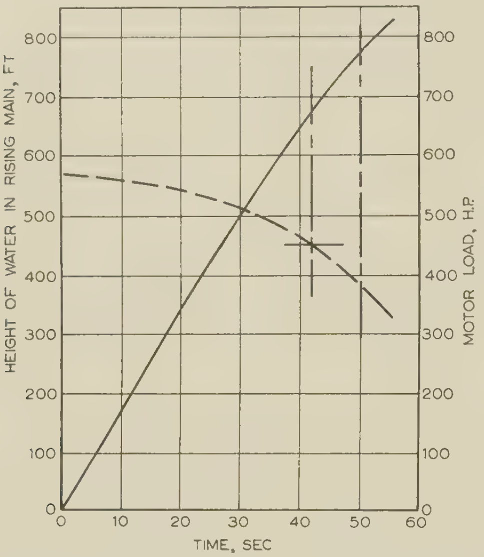

Fig. 15.—Variation in motor load and height of water column with time during filling of rising main.

—— Height of water in rising main.
---- Motor load.

h.p. load on the motor plotted against time. In this case, the total time taken to fill the rising main is 50 sec and the motor is overloaded for 42 sec. The r.m.s. load on the motor during the time it is on overload is 530 h.p., i.e. the motor is overloaded by 17·7% for 42 sec. The duration of this overload is short compared with the heating time-constant of the motor, so that the temperature rise due to this overload is of no practical significance even if the machine is warm when started up. Since the duration of the overload is short and the resultant heating of the motor is slight, approximate calculations are really all that is necessary in most cases.

If an attempt is made to start the pump set on too low a tapping of the auto-transformer, the speed/torque curves of pump and motor may either touch or cross, as shown in Fig. 13. When this happens, the motor will not accelerate to a higher speed until the conditions change. With the curves crossing at 830 r.p.m. the pump has a free discharge of 1 300 g.p.m. and will deliver this quantity of water straight into the rising main. As the water level increases in the rising main the pump torque for a given speed will fall, so that the pump set will increase slowly in speed. Without entering into detailed calculations it is clear that the time taken for the motor to run up to speed is enormously increased and will be longer than the time taken to fill the rising main when the motor has been started satisfactorily. The current taken by the motor, while this is happening, is virtually the starting current of the motor, and consequently there is a very serious risk that the motor winding will be overheated and damaged. Fortunately, this dangerous condition is easily recognized, because the ammeter will show that the current taken by the motor is remaining at its starting value for a much greater time than the two or three seconds of normal starting. This condition can be corrected by changing to a higher tapping on the auto-transformer.

(14) EXAMPLES OF SUBMERSIBLE DUTIES

Whilst the majority of submersible pump sets are supplied for use in mines and waterworks, there is, however, increasing adoption of this type for applications where absence of a gland is an advantage. Examples may be cited of boiler-circulating duties, water-supply pipeline boosting duties and the handling of liquids that are precious, toxic or inflammable. Here, the motor may contain the pumped liquid and may be built into the pipeline, so that no leaks are possible. For certain applications, a thin tube in the air-gap keeps the stator windings free of pumped liquid.

Submersible pump sets are applied to a variety of duties ranging from a two-pole motor of a few horse-power to large relatively slow-speed sets. Units as large as 450 h.p. at 1 470 r.p.m. and as high in head as 1 600 ft at 2 900 r.p.m. have been in operation for some years, but these duties by no means represent the limit of submersible pump-set design.

(15) ACKNOWLEDGMENT

The authors wish to thank the Harland Engineering Co. Ltd. for permission to publish the data in the paper.

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(17) APPENDICES

(17.1) Pump Efficiency and Specific Speed

The specific speed of the pump, given by $N\sqrt{Q}/h^{3/4}$, indicates the type of the pump, and is defined as the speed at which a pump would run if reduced geometrically to give a flow of 1 g.p.m. at 1 ft head.

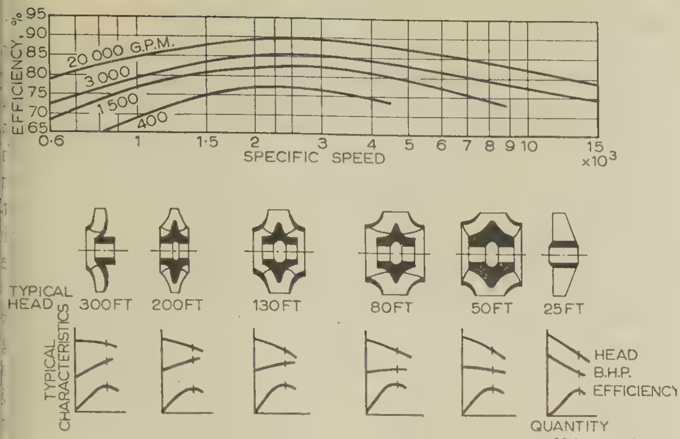
In general, the specific speed determines the shape of the impeller and chamber flow passages, and in consequence affects the efficiency.

Since the peripheral impeller velocity is the primary determinant of head, it follows that a higher specific speed in revolutions per minute would require a smaller-diameter wider impeller for the same head of 1 ft and the same quantity of 1 g.p.m.

The higher-specific-speed impeller has, therefore, a smaller diameter and relatively wider flow passages than an impeller of lower specific speed. It has, in consequence, lower disc-friction losses and, up to a certain optimum point, a higher efficiency, as shown in Fig. 16.[4] Beyond this optimum value of specific speed, efficiency falls off owing to inadequate guidance of flow.

(17.1.1) Variation of Efficiency with Quantity Pumped

A pump is a dynamic device for producing head (which depends on velocity squared) but it suffers from losses depending, according to Reynolds number, on velocity to a power in the



[*Morgan*, 1957

Fig. 16.—Specific speed, type of pump and characteristics.

neighbourhood of 1·7 to 1·8. Increase of size and speed will increase efficiency, since the dynamic head depending on velocity squared increases at a greater rate than the losses varying as $(\text{velocity})^{1\cdot 7}$ or $(\text{velocity})^{1\cdot 8}$. Reynolds number analysis, therefore, permits forecast of variations of efficiency for changes of size and speed.

Practical experience indicates that for the same specific speed (or proportional shape of pump) a small pump running at a high speed will give the same efficiency as a large pump running at a lower speed, provided that the flow quantity is the same in each case. The efficiencies of several pumps are therefore plotted directly against the flow in gallons per minute, and a consistent curve is obtained, the gallons-per-minute scale in place of the Reynolds number being sufficiently accurate from the point of view of efficiency assessment (Fig. 17).

Initially, the flow/efficiency curve was plotted and its mathematical formula evaluated. It was then replotted as a straight line on a logarithmic scale by separating the constant and the variable losses, as in Fig. 17.

Two vertical scales are shown in Fig. 17, efficiency and variable loss, but the true logarithmic scale is given by the latter. Each point on the graph is the average result for all the pumps made of that particular size and specific speed, the chart representing a bulked analysis of several thousand pumps.

(17.1.2) Efficiency: Quantity Formula.

The curve of Fig. 17 is similar to the variable portion of the Reynolds-number/pipe-friction curve.

The solution of the flow/efficiency curve can be expressed mathematically as follows:

$$1 - \eta = Q^{-0\cdot 32} + 0\cdot 06$$

By plotting $(0\cdot 94 - \eta)$ against Q, a straight-line graph can be obtained on logarithmic paper, as in Fig. 17. This suggests that 0·06, or 6%, of the losses are constant, independently of flow or of Reynolds number. The above equation can be transposed to $1 - \eta =$ total losses, where 0·03 of the losses are fixed (disc friction glands, bearings and leakage), 0·03 are due to the constant friction head and $Q^{-0\cdot 32}$ is due to variable friction head. The last two terms, $0\cdot 03 + Q^{-0\cdot 32}$, covering the pipe-friction portion of the loss, are of similar form to the expression for Reynolds pipe-friction curve by Stanton and Pannell[5,6]:

$$\tfrac{1}{2}\mu = 0\cdot 0009 + 0\cdot 0765\, R^{-0.35}$$

where R is the Reynolds number.

We have thus separated the various losses in the pump, the major loss being passage friction (i.e. pipe friction).

(17.1.3) Moody Efficiency Step-up Formula.

The Moody step-up formula for water turbines using an index of $\frac{1}{5}$ is shown as the dotted curve in Fig. 17, to compare with the above formula.

The Moody formula states that the losses in a hydraulic machine vary inversely as the one-fifth power of the size. An infinitely large machine formula would therefore have 100% efficiency on the Moody formula compared with 94% on the authors' formula.

(17.2) Complete Characteristics and Transient Phenomena of Pump Set

In order to avoid pipe failure and to determine overspeeds following power failure, it is necessary to investigate transient phenomena.

(17.2.1) Rotational Inertia of Motor and Pump.

The mechanical time-constant is used to describe the relationship between the kinetic energy at normal speed of the complete rotor and the power taken to drive the pump at normal duty. Dividing the kinetic energy by the horse-power, the mechanical time-constant, in seconds, becomes

$$\tau = \frac{wk^2N^2}{P_m \times 3\cdot 22 \times 10^6}$$

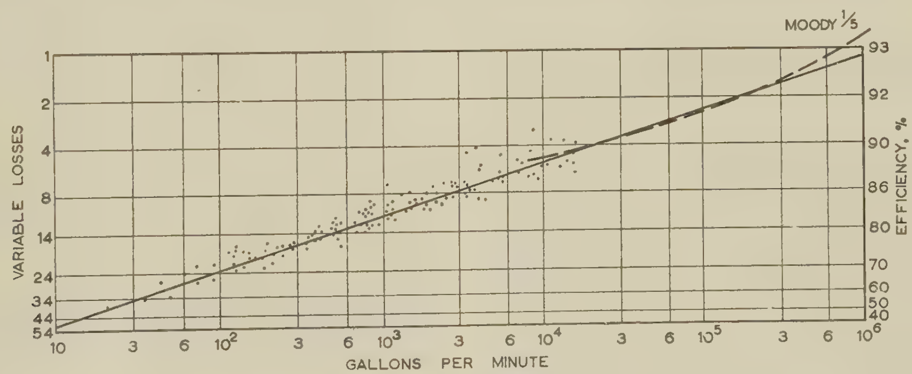


Fig. 17.—Pump efficiency at optimum specific speed.

(17.2.2) **Inertia of Pipe Column.**

The stopping time of the flow in a simple pipe will be a period of seconds after power failure, expressed as:

$$\text{Stopping time} = \frac{lv}{gh_r}$$

Fig. 18 illustrates, on a time basis, the performance of pump and pipeline after power failure has occurred.

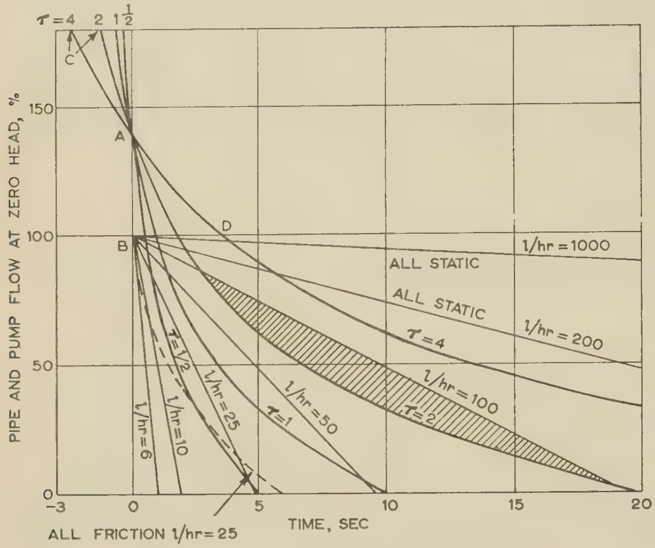


Fig. 18.—Pump and pipeline stopping times.

Shaded area represents cavity.
A, Mean point assumed to be approximate starting-point of column retardation.
B, Typical equivalent point of pipe-flow deceleration, taking into account pump energy above 100% flow only.
C, Points of power failure. Full pump flow and head maintaining full column flow at these points.
D, Full pump flow but at zero head. Pump cannot maintain full flow of column.

The heavy lines labelled with various values of the time-constant on Fig. 18 represent the quantities that the pump is capable of delivering against zero head plotted against the time after power failure.

In general, the danger of column separation occurs when the pressure falls below zero head and approaches a vacuum of 33½ ft, at which vaporization of cold water occurs.

The adoption of zero head (atmospheric pressure) as a reference thus contains a margin of safety above actual water-column breakage and also avoids risk of pipe collapse under vacuum where very thin pipes are involved.

The τ-curves were drawn by plotting the speed/time curve of the pump when it is allowed to reduce from full speed to zero speed after a power failure. This is based on an integration wherein kinetic energy is converted to pumping energy. The speed/time curve of Q, starting from 100% pipe flow and falling to zero, is then multiplied by $1\cdot 8$ to give the equivalent flow curve of the pump at zero head, since zero head on the average pump will give a flow of approximately 180% of normal flow. The power at $1\cdot 8$ times normal flow is assumed in the general case to equal normal flow power. We then have a curve of the flow capabilities of the pump on zero head.

The fine lines in Fig. 18 represent the time taken for various columns to stop on power failure, the characteristic being, in the general case, a series of straight lines having varying values according to the ratio of pipe length to operating head. These values of l/h_r are indicated on the lines.

In Fig. 18 the pipeline characteristics all start at a point which is to the right of the starting-points of the pump characteristics. This is to allow for the energy given by the pump to the pipeline flow after power failure.

(17.2.3) **Example 1.**

A pump set has $\tau = 2$ sec and a pipeline $l/h_r = 100$. Approximately 6 sec after power failure, a cavity will occur in the pipe, for which an air and water pressure tank having a water capacity equal to the shaded area in Fig. 18 is recommended. The pressure in the tank after the water has filled the cavity should be high enough to avoid vacuum at any peak in the pipeline. This pressure is determined by drawing a straight line from the final reservoir level to touch the highest pipeline peak and to meet a vertical line from the pump house on the elevation drawing of the pipeline. The point of meeting determines the minimum safe pressure at the pipeline entry.

(17.2.4) **Example 2.**

A pump set has $\tau = 0\cdot 5$ sec and pipeline $l/h_r = 10$. Here no danger of a cavity occurring exists as the τ-line is well to the right of the l/h_r line in Fig. 18.

(17.2.5) **Size of Pressure Vessel: Approximate Formula.**

No cavity occurs if wk^2 is equal to or greater than x, where

$$x = \frac{lvP_m}{h_s + \frac{1}{2}h_f}\left(\frac{100}{N}\right)^2 \times 1\cdot 7$$

If wk^2 is less than x, the water capacity of the surge vessel is $(x/wk^2) - 1$ seconds of full flow for the cavity only.

Larger vessel may be required to limit surge pressure.

(17.2.6) **Make-up of Head.**

The straight fine lines of Fig. 18 represent wholly static heads, and the dotted line represents a typical wholly frictional head. These lines are based upon a typical pipeline flow velocity of 6 ft/s.

DISCUSSION BEFORE THE UTILIZATION SECTION, 12TH NOVEMBER, 1959

Mr. H. R. Lupton: During the war the Metropolitan Water Board used a number of fairly large pumping units having submersible motors which were encased in a steel shroud which formed part of the water circuit. These units could be used vertically, horizontally or in any other position and, being self-contained, could very expeditiously be installed for use below ground or on the surface.

Why, as the authors state, is the submersible pump primarily a multi-stage pump? Not long ago a client needed some low-head pumps (13 ft) for lifting surface water into a reservoir. The pumps had to be accommodated in a wet pit. No British manufacturer would quote for suitable axial-flow submersible sets, and we had therefore to obtain them from abroad; these have given complete satisfaction.

By forcing air into the motor, it might be possible to avoid the loss in efficiency (some 4–8%) which results from the viscosity of the water in the air-gap. It might also be possible to improve the power factor, depressed in the present design by the necessity (in a water-filled motor) to ensure smooth surfaces, by the use of tunnel windings involving a large leakage flux. In fact, the power factor is also depressed by the necessity, with the long and thin rotors inevitable in borehole pumps, of an air-gap

larger than in ordinary motors. Data on the power factors actually achieved would be very interesting.

The air would be introduced during running periods from the surface through a tube at a rate greater than it would escape (at low differential pressure) through the seal at the top of the motor, the surplus escaping through a small non-return valve near the bottom of the motor carcase. Enough water could be left within the motor—or could be continuously introduced with the air—to ensure the lubrication of the bearings. The cooling of the windings would of course have to be ensured, but with ingenuity this could be achieved without water logging the air-gap.

Regarding the capacity of the p.v.c. of the windings to sustain load when warm, will the magnetic force on the conductors themselves in time cause deformation? The authors state that the overhung part of the windings must be braced against magnetic, and also hydraulic, forces. What were these hydraulic forces?

In Section 9 it was claimed as an advantage of the submersible pump that no housing was required for the motor. This would apply also to a spindle pump if driven by a weatherproof motor.

It is interesting that experience of a great number of tests on a great number of units could be as succinctly epitomized as in Fig. 17, and that a graph could be plotted which was independent of head. Correlation with Stanton and Pannell's work, however, seems doubtful, since their scale, the Reynolds number, is proportional to νD, whereas the abscissae of which the logarithms were plotted in Fig. 17 were proportional to νD^2.

Mr. G. P. E. Howard: We do not agree on the carrying capacity of journal and thrust bearings, which we normally rate conservatively at 400 lb/in². It is about 15 years since we provided any hydraulic balancing in our motor pumps and the whole hydraulic load is carried on the motor thrust bearing.

In Section 10.1 it is stated that journal bearings are lightly loaded. This is true when the rotor is coaxial, but if bearing clearances increase, theory suggests that the unbalanced magnetic pull may rise to a high figure. However, in submersible motors there appears to be a difference between theory and practice of a factor of nearly 10.

Fig. 11 gives an unnecessarily alarming view. What is important is the electric strength which, at 60° C, is 70% of that at room temperature. In consequence, these units may be flash-tested hot without damage, but measurement of the insulation resistance hot may cause a perfectly sound motor to be withdrawn by the inexperienced.

Wherever possible we start our motors direct on line. The starting time is short: a 350 h.p. high-voltage 4-pole motor takes its full starting current for 30 cycles and is up to speed in 50; a 1 000 h.p. 4-pole motor takes 80 cycles to reach full speed. Small 2-pole motors come up to speed even faster. We have had no trouble with the end turns chafing when using direct-on-line starting.

Mr. C. A. M. Thornton: We have used submersible motors for 25 years. The early difficulties have been overcome and the motor life now equals the pump life of approximately seven years' continuous running. Lamination corrosion was the most serious difficulty. This is now minimized by keeping the internal water separate from the external. Some of the rotors are also sleeved with non-magnetic stainless steel. Chromium plate and vitreous enamel, and also an unlaminated rotor with a normal cage, have been tried. Stator lamination corrosion may be even more troublesome than rotor corrosion. All our motors are supplied at 500 volts and we have found p.v.c. and polythene insulation satisfactory. Rubber was used in the early motors but did not have such a good life as p.v.c. For bearing sleeves, white metal, asbestos and phenolic proprietary products have all been used successfully. There may be a greater danger of shaft pitting with white-metal sleeves. We have not been troubled consciously by unbalanced magnetic pull but a long motor of small diameter is always more prone to this, and it is better not to rely on the laminations supporting the shaft as they may cease to do so when warm, unless assisted by corrosion, owing to unequal expansion of shaft and laminations.

The skin of fluid vortices in the air-gap shown in Fig. 7 is an important but sometimes forgotten feature of fluid-filled motors. This skin offers great resistance to the passage of fluid axially along the gap and if an unwary designer assumes a free passage for fluid he may find a thrust bearing unexpectedly overloaded. This skin also probably has a considerable steadying effect on a rotor running near its critical speed (Section 11). Rotor windage in a fluid-filled motor varies as the fifth power of the rotor diameter and may therefore attain an unexpectedly high value.

Mr. F. Wood: I am with the Metropolitan Water Board, who are large users of submersible pumping plants, and I propose to make a few remarks about maintenance. As in Mr. Thornton's case, our plant runs continuously, usually for 12 months or more. We have between 50 and 60 of these units, some of which are of the type described by the authors and some of the dry type. Of the total number of our motors, about half are in continuous use. Over about 1 000 000 running hours, the average life between major overhauls is about 17 000–18 000 hours, being about the same for both the dry and wet types of motor. Since the units have been overhauled we have had about 200 000 hours with those in service now.

The longest running record we have is with a dry-type motor which is still running now after 80 000 hours. We intend to leave it running until it breaks down.

We try to do our own maintenance work, and have found it is much easier to repair the wet type than the dry, with which we have had a great deal of trouble.

Although some of the units use a solution of oil and water as a coolant, we specify that all our units must be filled with distilled water as coolant.

Mr. Lupton referred to horizontal motors. We often use them, as they are very flexible, and we always specify now that the units which we buy must be capable of running horizontally or vertically.

Foot valves were fitted on our early units, but we have eliminated them. We found that the head lost through them was very high indeed and we were having to take pumps out of the borehole or well merely to repair the foot valves. We therefore fit the normal non-return valve at the surface and the rotor must be designed for excess rotational speed in the opposite direction.

From some figures obtained in 1955 I find that where we have two units, one a spindle unit and one submersible, doing exactly the same duty, namely 120 b.h.p., the price including capital cost is in the ratio of 3 : 4 (submersible pump to spindle pump) for a well depth of 180 ft, but as the depth decreases the costs become more nearly equal, until at a depth of 80 ft or less, the spindle pump is cheaper. However, the running costs (excluding labour) for fuel and maintenance generally, electrical and mechanical, are approximately 2d. per horse-power-hour for the submersible pumps and 2¼d. for the spindle pumps.

Mr. D. Purves: With regard to thrust-bearing design, Walker* quotes a specific loading of 300 lb/in² for reversible-type bearings and 400 lb/in² for unidirectional bearings, where these are of the oil-lubricated type. Subsequent discussion on this paper revealed that the latter figure might be raised to 600 lb/in² on occasion.

The authors confirm that with a water-lubricated bearing

* See page 157.

designed for submersible pumping duty the specific loading should be lower than usual practice. What is the authors' opinion regarding the very high figure quoted by Mr. Howard?

Mr. J. Tozer: When one buys a motor one expects to buy a cable box. If a motor is put a long way down in a borehole we need more information about the cable box. Will the authors comment?

Mr. R. C. Worster: The information given by the authors in Fig. 17 on the variation of pump efficiency with delivery is very valuable, not only as a guide to pump performance but also as a contribution to the subject of scale effects in pump testing. Is the comparison between the effects of delivery on pump losses and the effects of Reynolds number on the pressure losses in pipe flow valid?

In comparison with the range of Q in Fig. 17, velocity can be taken as constant, so that pump size, D, is proportional to $\sqrt{Q}$ and a pump Reynolds number comparable with that used for pipe flow will be proportional to $\sqrt{Q}/\nu$. The equation for relating η and Q will then be equivalent to $(0{\cdot}94 - \eta) \propto (\sqrt{Q}/\nu)^{-0{\cdot}64}$ In this form the equation exposes two difficulties in the interpretation of Q-effects as Reynolds-number effects: pump losses appear to vary with Reynolds number at about twice the pipe-friction rate, and the apparent effects of viscosity are far greater than practical experience on pump performance justifies.

Another approach is to consider the effect of Q on pump losses as representing that of roughness on pipe friction. The authors' equation can equally well be interpreted as $(0{\cdot}94 - \eta) \propto (Q/e^2)^{-0{\cdot}32}$ or $(0{\cdot}96 - \eta) \propto (D/e)^{-0{\cdot}64}$, where e is the roughness height on the walls of the impeller and the casing and would tend to remain constant irrespective of pump size. This approach avoids the difficulty over viscosity effects but it still does not compare very well with pipe friction, which varied with relative roughness more as $(e/D)^{0{\cdot}3}$.

It might be concluded that there must be other effects present in the influence of Q on pump efficiency besides those of viscosity and wall roughness: these might include the lack of geometrical similarity with respect to details such as impeller blade and shroud thickness.

Mr. H. Davies (*communicated*): The possible characteristics of the stator insulation for a submersible motor would be provided by encapsulating the stator winding in a filled epoxy resin. I understand that this is done by some firms on the Continent. Have the authors tried this method of insulation and have they any comments on its suitability?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. H. H. Anderson and **W. G. Crawford** (*in reply*): In reply to Mr. Lupton it is regretted that the paper implied that submersible pumps were necessarily multi-stage. It would be more correct to say that they can be single stage or multi-stage, but that the single-stage unit would, for convenience of manufacture, comprise one stage of a multi-stage pump.

In reply to Mr. Worster, Fig. 17 represents a compounding of: a range of geometrically similar pumps with constant head, where the flow is proportional to diameter squared and the velocity is constant; of tests of single pumps at various speeds where the flow is proportional to velocity and diameter is constant; and of parallel ranges at different specific speeds which have been corrected to the optimum specific speed in accordance with Fig. 16. In spite of this complication, the flow/efficiency chart has a relatively small scatter of points.

Whilst agreeing with Mr. Worster that there must be other effects present in the influence of Q on pump efficiency besides those of viscosity and wall roughness, it is not thought that these are primarily due to lack of geometric similarity, since all the pumps shown were designed on the same basic principles.

The flow/efficiency curve of Fig. 17 is therefore an effective instrument, but its correlation with the Reynolds-number/pipe-friction curve involves further research for which Mr. Worster's suggestions are most helpful.

Mr. Lupton's suggestion that air be blown into a submersible motor is interesting but would require considerable development. Such development would be contrary to our present object, which is to have a motor with no connection to it other than the cable. The hydraulic forces acting on the end-winding are due to the whirling of the water, and experience has shown that careful bracing of the end-winding is necessary. The power factors of submersible motors are shown in Figs. A and B.

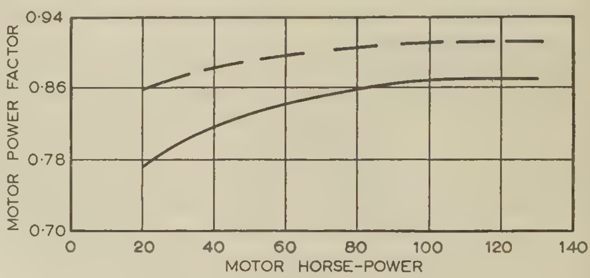


Fig. A.—Power factors of 2-pole submersible motors.

—— Two-pole submersible motors.
---- Four-pole slip-ring motors.

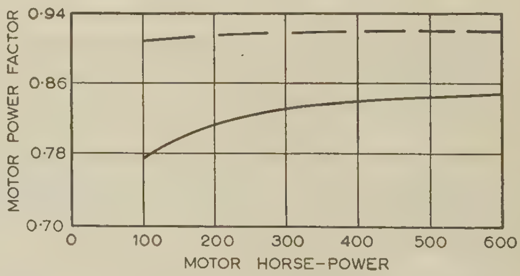


Fig. B.—Power factors of 4-pole submersible motors.

—— Four-pole submersible motors.
---- Four-pole slip-ring motors.

Mr. Howard's comments on pump and thrust-bearing design are most interesting and show how different lines of development can lead to equally satisfactory results. However, in reply to Mr. Purves, we must say that we do not think it would be advisable to base the design of submersible-motor thrust bearings on experience derived from water-turbine-driven alternators because of the great differences between the two types of machine.

Mr. Tozer will be interested to know that, in general, submersible motors do not have cable boxes. A short length of cable is connected to the motor windings and brought out through a gland in the motor end frame. This is then joined directly to the rising main cable.

The knowledge and experience of operating engineers is always of great value to the designer and consequently the comments by Mr. Thornton and Mr. Wood form a valuable addition to our paper. We have many ideas in mind for future developments, and although we have not so far tried encapsulating the stator winding, this possibility has not been overlooked.

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FIELD SUPPRESSION OF TURBO-ALTERNATORS

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SUMMARY

The paper is concerned with the field suppression of synchronous machines by means of a discharge resistor connected across the field winding and with the suitability of such a method for alternators of 100 MW and above. Expressions are given for the field current when a 3-phase fault is applied to the armature terminals, and also for the currents and voltages during field suppression. The effect of the discharge resistance value upon the field over-voltages, the field circuit-breaker arc duration and the stator fault damage is discussed.

Many field suppression tests have been made on turbo-alternators in conjunction with short-circuit tests on the alternator. Results of some of these are presented and are compared with values of theoretical expressions derived as illustrated in the Appendix.

The duty on the main and discharge contacts of the field circuit-breaker and methods of proving their suitability for the duties are considered. The use of a synthetic circuit for proving the interrupting capacity of the main contacts is unsuitable if the arcing time is long.

Other forms of field suppression are available. These may give improved field suppression but either require more complex circuits or are unlikely to be suitable for very large alternators.

It is concluded that the value of the discharge resistance should be determined by the permissible field over-voltage and circuit-breaker arc duration.

LIST OF SYMBOLS

I_{fd} = Field current.
I_{fdD} = Current circulating in field and discharge resistor during suppression.
I_B = Current associated with field circuit-breaker voltage.
I_s = Total current injected at field circuit-breaker to represent final clearance.
I = Armature current.
V_{fd} = Field voltage.
V_B = Voltage across field circuit-breaker during arcing.
V_d = Direct-axis machine terminal voltage.
V_q = Quadrature-axis machine terminal voltage.
V = Machine terminal voltage.
R_{fd} = Field resistance.
R_{kd} = Direct-axis damper resistance.
X_{ad} = Direct-axis magnetizing reactance.
X_d = Direct-axis synchronous reactance.
X'_d = Direct-axis transient reactance.
X''_d = Direct-axis sub-transient reactance.
X_{kd} = Direct-axis damper leakage reactance.
X_q = Quadrature-axis synchronous reactance.
X_l = Armature leakage reactance.
τ_a = Armature time-constant.
τ'_d = Direct-axis transient time-constant.
τ''_d = Direct axis sub-transient time-constant.
$\tau_{kd} = X_{kd}/\omega R_{kd}$.
$\tau_{kdo} = (X_{kd} + X_{ad})/\omega R_{kd}$.
$\tau_{kld} = \left(X_{kd} + \dfrac{X_{ad}X_l}{X_{ad} + X_l}\right)\Big/\omega R_{kd}$.
τ_α, τ_β = Time-constants defined by eqn. (20).
τ_B = Time-constant of field circuit-breaker voltage.
D = A measure of the energy dissipated at an armature fault point.
K = Discharge resistance value as a multiple of field resistance at operating temperature.
$L = [V^2 + VI(X_d + X_q)\sin\phi + I^2X_dX_q]/\sqrt{(V^2 + 2VIX_q\sin\phi + I^2X_q^2)}$.
= Field current for load condition as a multiple of that for full voltage open-circuit conditions (saturation neglected).
M = Maximum value of field circuit-breaker arc voltage as a multiple of unit field voltage (for rated open-circuit armature voltage).
t_2 = Time from short-circuit instant to start of field circuit-breaker arcing voltage.
t_3 = Time from start of field circuit-breaker arcing voltage to final clearance.
δ = Load angle.
ϕ = Power-factor angle.
$\sigma = (X_d - X'_d)/X'_d$.
$\lambda = X'_d(X''_d - X_l)/X''_d(X'_d - X_l)$.

(1) INTRODUCTION

In the event of a terminal short-circuit on an alternator the protective gear must operate so as to minimize the damage to the machine and the disturbance to the power system. Opening the main circuit-breaker will isolate the alternator from the system, but current will continue to be fed into any permanent fault until both the excitation current in the field winding and the stored magnetic energy in the machine are reduced to zero. In order to minimize the damage caused at the point of fault, it is desirable to achieve this condition as quickly as possible. However, the rapid interruption of the field current tends to result in excessively high voltages in the excitation circuit and, incidentally, is followed by a final period of fault-current flow associated with the dissipation of energy by currents circulating in damper windings, teeth, wedges and retaining rings. There are various ways in which controlled field suppression can be achieved, the general practice in this country being the use of a field circuit-breaker and discharge resistor. The circuit arrangement is shown in Fig. 1. The sequence of operations is that the discharge contact is closed just prior to the parting of the main contacts. Opening of the main contacts results in the connection of the discharge resistor across the field winding and the disconnection of the exciter from the field. The problem is thus selection of a suitable circuit-breaker and value of discharge resistance to give as rapid an energy dissipation as is consistent with the insulation strength of the field circuit, and the safe operation of the field circuit-breaker.

The authors are with The English Electric Co., Ltd.

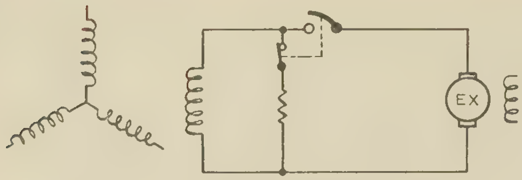

Fig. 1.—Typical field-suppression circuit.

The increasing ratings of individual alternators make it more important than ever to limit the damage in the event of a stator fault, and thereby to minimize the possibility of a lengthy and expensive outage. Fig. 2 shows how the excitation requirements for turbo-alternators have increased with the generator ratings and with improved methods of cooling. The choice of suitable field-suppression equipment becomes progressively more critical.

It is the purpose of the paper to consider these requirements in the light of practical tests and theoretically derived results.

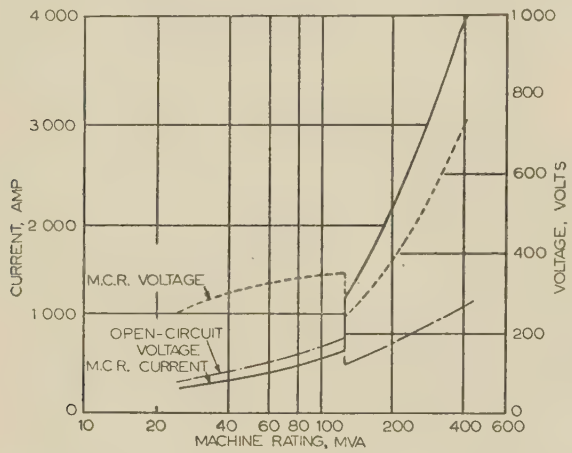

Fig. 2.—Variation of excitation current and voltage with rating of turbo-alternator.

(2) THE FIELD CURRENT RESULTING FROM ARMATURE SHORT-CIRCUIT

When a fault occurs at the terminals of an alternator, large currents flow transiently in the windings, large transient components of torque are associated with them, and, in addition, the automatic voltage regulator may initiate a change in excitation. Field suppression begins to be operative within 0·1 sec, and therefore changes in speed and in exciter voltage may reasonably be neglected.

In the case of a symmetrical 3-phase short-circuit, each armature phase current contains transient a.c. components and a transient d.c. component. These are associated respectively with transient d.c. components and a transient a.c. component in the field circuit, superimposed upon the initial field current flowing before the fault. An example of these currents is shown in Fig. 3 for the case of an alternator excited to produce rated open-circuit voltage. The additional field current reaches a peak several times the steady-state value.

Under the most general unsymmetrical fault conditions the additional transient field current may contain transient d.c. components together with transient a.c. terms of fundamental frequency and also harmonics. It would be possible to study particular cases of such faults by numerical methods and to represent the operation of field suppression analytically, but for the purpose of the paper attention has been restricted to the 3-phase case. For normal values of the machine parameters this represents the most arduous duty for the field circuit-breaker.

The additional field current for a 3-phase terminal short-circuit from rated open-circuit voltage (see Section 15) is given by

$$I'_{fd} = \sigma\left[\exp\left(\frac{-t}{\tau'_d}\right) - (1-\lambda)\exp\left(\frac{-t}{\tau''_d}\right) - \lambda\exp\left(\frac{-t}{\tau_a}\right)\cos\omega t\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the machine were initially at rated voltage and full load the additional field current is approximately

$$I'_{fd} = \sigma\left\{\cos\delta\left[\exp\left(\frac{-t}{\tau'_d}\right) - (1-\lambda)\exp\left(\frac{-t}{\tau''_d}\right)\right] - \lambda\exp\left(\frac{-t}{\tau_a}\right)\cos(\omega t+\delta)\right\} \quad . \quad (2)$$

In eqns. (1) and (2), I'_{fd} is expressed in per unit of the field current required for rated voltage on open-circuit. It will be seen that the transient field current comprises d.c. components having the alternator transient and sub-transient time-constants, and an a.c. component having the armature short-circuit time-constant.

For the machine constants listed in Section 15.1, values of I'_{fa} have been calculated corresponding to short-circuits from (*a*) open-circuit and (*b*) load conditions. For (*a*), I_f is

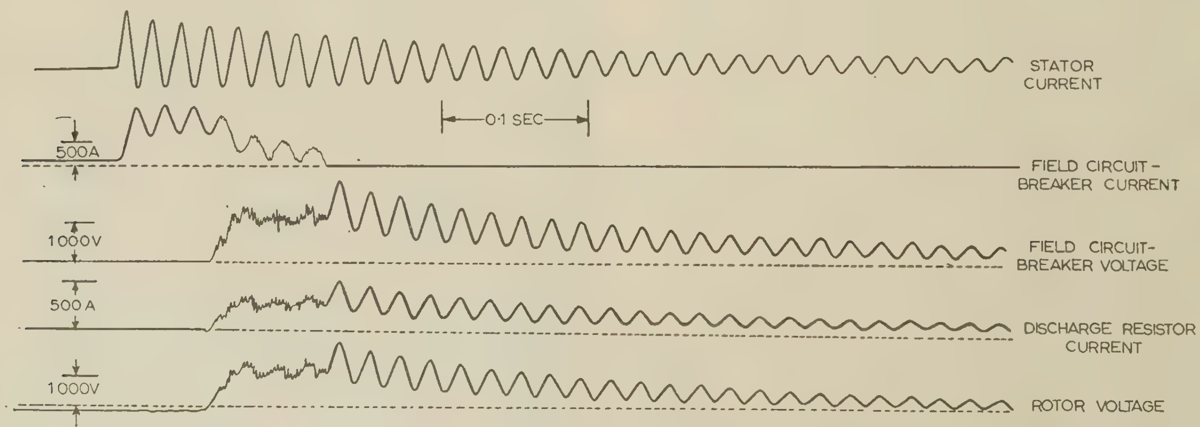

Fig. 3.—Oscillogram of field-suppression test on turbo-alternator when short-circuited.

Machine E excited to rated voltage on open-circuit and with discharge resistance equal to 5 times the hot field winding resistance.

initially 1·0 per unit and for (b) it is given by the quantity L (neglecting saturation) which in this case is 2·91 per unit. Values of I'_{fd} after about 0·1 sec are (a) 6·0 ± 1·35 and (b) 4·8 ± 1·35; thus, the total field current at this time is (a) 7·0 ± 1·35 and (b) 7·71 ± 1·35. In these terms the plus sign relates to a maximum and the minus sign to a minimum of the oscillatory component. The peak value for case (b) is 9·06/2·91 or 3·12 times the m.c.r. field current.

(3) THE CHARACTERISTICS OF THE D.C. CIRCUIT-BREAKER

Before considering in detail the properties required of a circuit-breaker for field suppression duty or the proving of such a breaker, it is advantageous to study the general characteristics of d.c. circuit-breakers.

An air circuit-breaker opening in a d.c. circuit carrying current can be best considered as a source of back-e.m.f. being injected into the circuit. In an inductive circuit, that is one having a time-constant of, say, at least 30 millisec, the value of this injected e.m.f. can be considered in three distinct stages.

Stage 1.—Immediately the contacts of the circuit-breaker part and an arc is struck, the e.m.f. rises as the arc lengthens. For a period of, say, 15 millisec the e.m.f. is changing at first relatively slowly, and then more quickly, until a peak is reached.

Stage 2.—Throughout this period the injected e.m.f. remains reasonably constant at an average value slightly less than the peak value at the end of stage 1. The more efficient the arc chute, the closer the control of the arc, and the more constant the injected e.m.f. will be. Throughout this stage, the energy of the circuit inductance is being dissipated in the arc, as is also the excess energy supplied by the source over that dissipated by the circuit resistance, and the current through the circuit is being reduced.

Stage 3.—When the current has been suppressed to a sufficiently low value, the arc in the chute becomes unstable and final interruption occurs, possibly with a higher peak e.m.f. in evidence.

A particular circuit-breaker applied for field-suppression duty will produce a steady e.m.f. during stage 2, which may be considered to be independent of the circuit parameters and of the current being interrupted. In the analysis of the operation, the increase in voltage described in stage 1 has been approximately represented by considering the rise to be exponential with time-constant τ_B. This does not correspond precisely to the form actually observed, but it is considered desirable to simulate some delay in the appearance of full voltage, rather than to apply a step-function, and the exponential expression is a simple means of doing so.

The arcing time is determined by the relationship of the circuit-breaker voltage to the circuit parameters. The analytical concept, used in Section 4, is that the breaker e.m.f. produces an opposing current to that flowing in the circuit until the instantaneous sum of these currents is approximately zero. Under some extreme conditions this may occur before the full circuit-breaker voltage is developed by the arc fully entering the chute, in which case stage 1 is followed by stage 3, and stage 2 is not in evidence. At the other extreme, the arcing time may be prolonged because the circuit-breaker e.m.f. is insufficient for the duty. The maintenance of a constant voltage across the arc depends upon the deionizing effect of the chute remaining uniform. In a modern arc chute the arc is confined and the deionizing effect is a function of the temperature of the material in contact with the arc. If this material is allowed to become too hot, the deionization of the arc is reduced and the e.m.f. drops. The rate of decrease of the total circuit current is lowered and the effect is cumulative, leading to failure of the interruption.

It is therefore essential to choose an interrupting device or circuit-breaker which will produce sufficient arc voltage during stage 2 to cause the current to fall rapidly enough for final interruption to occur before the e.m.f. produced by the arc falls in value. To obtain a short enough arcing time in a highly inductive circuit, an arc chute capable of producing a relatively high e.m.f. is necessary.

Further, when the circuit-breaker is mounted inside a cubicle, it is essential to ensure that the arcing period is limited to prevent a build-up of ionized gas in the cubicle, otherwise flashovers to earth may occur.

In the authors' opinion the maximum arcing time which should be considered under these conditions for alternators from 60 MW to 200 MW is 60 millisec. Longer arcing times are allowable for smaller alternators, but shorter arcing times would almost certainly need to be considered for larger alternators.

(4) CONDITIONS DURING FIELD SUPPRESSION

(4.1) Field Currents

When field suppression is initiated, the discharge resistor is connected across the rotor winding and the current in the discharge resistor builds up to a value determined by the exciter voltage and the discharge resistance. Since the time-constant of this circuit is of the order of 0·005 sec, it is convenient for the purpose of the mathematical analysis to assume that the current builds up instantaneously to a value L/K per unit of the base field current.

Following the connection of the discharge resistor, the main contacts of the field breaker part and, in effect, a voltage is injected into the circuit as described previously. It is convenient for the analysis to assume that the voltage injected during stages 1 and 2 of the circuit-breaker operation can be represented by the equation

$$V = MV_{fd}\left[1 - \exp\left(\frac{-t}{\tau_B}\right)\right] \quad . \quad . \quad . \quad . \quad (3)$$

τ_B being of the order of 10 millisec or less.

The current that results from the application of this voltage to the circuit as seen from the circuit-breaker terminals, i.e. the discharge resistor in parallel with the rotor winding and the stator winding short-circuited, is shown in the Appendix to be approximately given by

$$I_B = M\left[1 + \frac{1}{K} - \exp\left(\frac{-t}{\tau'_d}\right) - \frac{1}{K}\exp\left(\frac{-t}{\tau_B}\right)\right] \quad . \quad . \quad (4)$$

This current is in the opposite direction through the circuit to the sum of the discharge resistor current and the field current. When the sum of all three currents is zero, the first opportunity occurs for the circuit-breaker to interrupt the circuit, which in this case corresponds to the successful transfer of the field current into the discharge path and the disconnection of the exciter. Assuming that this is effected at a minimum of the oscillatory component, and that the sub-transient term in the field current has decayed to negligible magnitude, then the following equation relates the various quantities and the arcing time, t_3:

$$L\left(1 + \frac{1}{K}\right) + \sigma\left[\exp\left(-\frac{t_2 + t_3}{\tau'_d}\right) - \lambda\exp\left(-\frac{t_2 + t_3}{\tau_a}\right)\right]$$

$$= M\left(1 + \frac{1}{K}\right) - M\left[\exp\left(\frac{-t_3}{\tau'_d}\right) + \frac{1}{K}\exp\left(\frac{-t_3}{\tau_B}\right)\right] \quad . \quad (5)$$

(4.2) Arc Duration

Eqn. (5) can be used to calculate arcing time as a function of K and M if values are given to the remaining terms. Using the values given in Section 15.1, the relationships shown in Fig. 4 have been computed. The machine parameters are typical of a 200 MW turbo-alternator, but the ratios σ and λ are also fairly representative of smaller machines and the values of τ_d' and τ_a are also of the same order as for lower ratings. The figures are not representative of water-wheel alternators.

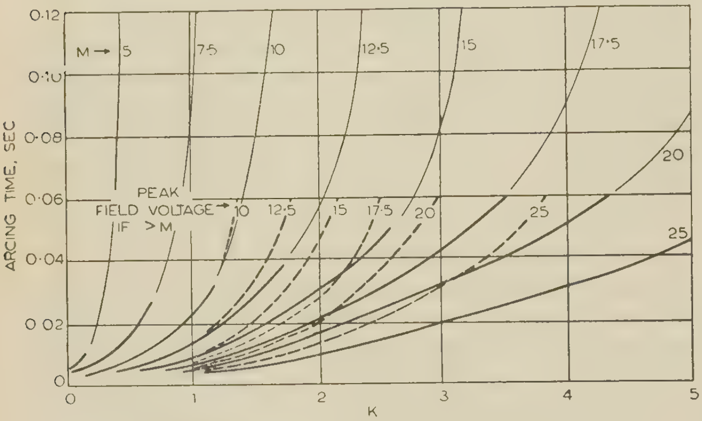

Fig. 4.—Arcing times, voltages and discharge resistances.

Fig. 4 shows clearly that, for the values indicated, arcing times become rather indefinite above particular values of K for any given value of M. For example, considering a circuit-breaker of $M = 12\cdot5$, it would be inadvisable to use a value of K greater than $1\cdot8$. The curves have been broken at such points, or where they exceed the value $0\cdot06$ sec suggested at the end of Section 3 as an upper limit. The dotted lines in Fig. 4 relate to maximum field voltages and are discussed in Section 6.

(4.3) Field Current after Transfer to Discharge Path

An approximate expression for the current I_{fdD} in the field winding and discharge resistance after clearance by the field circuit-breaker, measuring time from the moment of clearance, is

$$I_{fdD} = \frac{M-L}{K}\exp\left(\frac{-t}{\tau_\alpha}\right) - \sigma\lambda\exp\left[-\frac{(t_2+t_3)}{\tau_a}\right]\left[\exp\left(\frac{-t}{\tau_a}\right)\cos\omega t - \exp\left(\frac{-t}{\tau_\alpha}\right)\right] \quad . \quad . \quad . \quad . \quad (6)$$

Comparing this with the equation for the field current before field suppression was initiated, it will be seen that the time-constant of the decrement of the oscillatory component has not changed whilst that of the d.c. component has changed from τ_d' to τ_α, i.e. to $\tau_d'/(K+1) + \tau_{kld}$. It can be shown that a corresponding change occurs in the rate of decay of the armature currents.

(5) FAULT DAMAGE IN THE STATOR

(5.1) Types of Fault

The most serious type of fault as regards the damage caused is an earth fault in the slot portion of the stator winding. This will result in arcing between the conductor and the core and burning of the stator laminations. The severity of the damage will then determine whether it is necessary to strip and rebuild the core.

Most modern large alternators are connected solidly to a step-up transformer, in which case it is not necessary to solidly earth the alternator neutral point and the usual practice is to earth it through an impedance of some kind. The earth fault current and the extent of the damage to the core are then limited. There is always the possibility that an earth fault occurring in a slot containing conductors of different phases may develop into a phase-to-phase and earth fault, resulting in a much larger fault current and possibly in greater damage of the core.

In cases where it is necessary to solidly earth the neutral point of the alternator, full phase-to-neutral short-circuit current would flow on an earth fault occurring at the line end of the phase and the amount of damage sustained by the stator core would be relatively much greater.

The other type of fault which should be considered is a phase-to-phase fault in the stator end-windings. The fault current may be large and may cause considerable burning of the affected conductors. The subsequent repair will involve the removal and replacement of part of the stator winding, but this is a simpler and less expensive operation than the rebuilding of the core which might be necessary after an earth fault.

(5.2) Estimation of Core Damage and Influence of Discharge Resistance

There are so many variables involved that the calculation of the amount of damage to the stator core likely to result from a fault is extremely difficult. Stator winding faults are rare and thus there is little evidence to support any method of calculation

The assumption of approximate proportionality between the amount of core burnt away and the energy fed into the fault permits a rough assessment of the relative damage from fault currents of varying durations. Further, since the voltage drop in the fault arc is constant for all but the smallest-magnitude fault current, the energy dissipated in the fault, and thus the quantity of core burnt away, can be assumed to be proportional to $\int_0^t |I|dt$, where I is the fault current and t is the length of time for which the fault persists.

Energy will be fed into a stator fault from the alternator itself and also from the system until the alternator is automatically disconnected from the system. The alternator's own components comprise the energy supplied by the alternator up to the time when field suppression is initiated, plus the energy supplied in the time during which the field is being suppressed. These quantities of energy for a 3-phase symmetrical fault at the alternator terminals are represented by the areas under the current/time curve, as shown in Fig. 5. It is only the energy supplied by the alternator during the suppression of the field that can be affected by varying the value of the discharge resistance.

As shown in the Appendix, the damage to the stator resulting from a 3-phase fault is given approximately by

$$D = \frac{V}{x_d}\frac{2}{\pi}\tau_d'\left\{\sigma\left[1-\exp\left(\frac{-t_2}{\tau_d'}\right)\right] + \frac{t_2}{\tau_d'}\left(1+\frac{x_d}{x_t}\right) + \frac{1}{K+1}\left[1+\sigma\exp\left(\frac{-t_2}{\tau_d'}\right)\right]\right\} \quad . \quad (7)$$

where x_t is the reactance between the alternator and the infinite busbar of the system, and t_2 is the time between the occurrence of the fault and the simultaneous tripping of system and field circuit-breakers.

This estimate of damage at a 3-phase fault is only approximate since it neglects, in order of relative importance, the asymmetric,

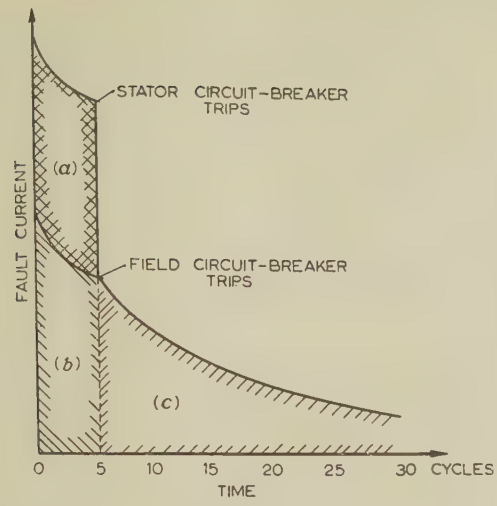

Fig. 5.—Contribution of energy from system and machine into fault.

(a) Energy supplied by system.
(b) Energy supplied by machine before field suppression.
(c) Energy supplied by machine during field suppression.

sub-transient and double-frequency components of fault currents. These last two make little difference to the results, but the d.c. component is more important. The value of the energy per cycle supplied by the alternator with a completely asymmetrical wave and no decrement is 57% greater than with a symmetrical wave. In practice the d.c. component decays with the armature time-constant, τ_a, which is considerably less than the time-constant τ_d', and consequently the error over a period of time in practice is much less than 57%. Furthermore, any fault involving flash-over of the insulation will inherently have small asymmetry in the currents.

The variation of damage, D, with the value of discharge resistance, K, is shown in Fig. 6, the values having been calculated for a typical alternator and transformer having $(x_d + x_t)/\sigma x_t = 3$ and $\sigma = 7$. These curves have been related to the case $K = 0$ and $t_2 = 0$ as unit value.

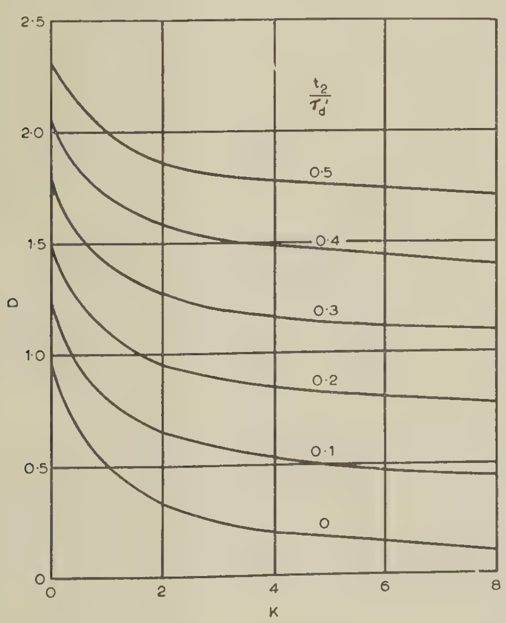

Fig. 6.—Variation of stator fault damage with value of discharge resistance.

It will be seen that the change in the discharge resistance has relatively little effect on the amount of damage except at the lower values of K and even less effect if the tripping of the circuit-breaker is slow (i.e. if t_2 is great).

(6) MAXIMUM FIELD VOLTAGES

Until the field circuit-breaker contacts part, the voltage across the field winding is the exciter voltage. When the contacts part, a voltage is introduced into the circuit and the voltage across the field winding is then the circuit-breaker voltage less the exciter voltage. If the circuit-breaker has developed its full voltage, M, and the machine was originally at rated load, the field voltage during arcing is $M - L$. After the circuit-breaker has interrupted the circuit, a higher recovery voltage is likely, the maximum voltage occurring when the oscillatory component of current reaches its next instantaneous peak value following clearance by the circuit-breaker.

An approximate expression for the voltage across the field, measuring time from the moment of clearance, is

$$V_{fd} = (M - L)\exp\left(\frac{-t}{\tau_\alpha}\right) - K\sigma\lambda\exp\left(-\frac{t_2 + t_3}{\tau_a}\right)\left[\exp\left(\frac{-t}{\tau_a}\right)\cos\omega t - \exp\left(\frac{-t}{\tau_\alpha}\right)\right] \quad . \quad (8)$$

The maximum value of this expression is approximately

$$M - L + 2K\sigma\lambda\exp\left(-\frac{t_2 + t_3}{\tau_a}\right) \quad . \quad . \quad . \quad (9)$$

This corresponds to the peak of the alternating component of field current which follows its transfer to the discharge path, as can be seen in the field voltage trace in Fig. 3. Whether or not this peak voltage impressed across the field circuit exceeds M depends on the relative magnitude of L and the last term in eqn. (9).

It is possible to calculate this relationship for any particular case and this has been done for the machine parameters mentioned in Sections 4.2 and 15.1.

The dotted curves in Fig. 4 show the transient recovery voltage across the field winding when it exceeds the value of M for the circuit-breaker. The recovery voltage is obtained as a per-unit value from the dotted curves by interpolation for any given pair of values of arcing time and K.

As far as the authors are aware, no evidence is available to show how voltages of this kind applied to the field winding are distributed between individual coils and between the turns of the winding and the earthed metal of the rotor. The determination of the distribution of voltage by tests would present considerable difficulties, but owing to the relatively large number of turns in the field winding, even with direct-cooled alternators, it is extremely unlikely that the inter-turn insulation would be stressed more severely than the insulation between any turn and earthed metal. As a means of proving this latter insulation, it is standard practice to apply a one-minute, 50 c/s high-voltage test between the field winding and earth as specified in B.S. 2613. This voltage is unlikely to be less than 3·5 kV r.m.s., except for the smaller machines, say up to 45 MVA, when it may be as low as 2 kV r.m.s. However, the associated field circuit-breaker, instruments, relays and control equipment normally have a high-voltage test applied at only 2 kV r.m.s. Thus, it appears to be undesirable to allow voltages having a peak value in excess of 3 kV on the field winding.

(7) TEST RESULTS

Tests have been made on several alternators to obtain experimental evidence showing the duty on the field circuit-breaker and the effectiveness of the field suppression with varying values of discharge resistance. These tests were carried out on typical alternators whose characteristics are listed in Table 1. The test results are given in Table 2.

Two tests of field suppression were made with machine A when the alternator was excited to normal voltage with the stator open-circuited. A typical oscillogram is shown in Fig. 7. Since there are no induced currents in the field winding, these tests do not give the worst conditions with regard to the circuit-breaker duty or to the over-voltage produced across the field winding.

The worst conditions arise when the machine is on load and a fault occurs on the stator terminals. It is obviously undesirable to carry out tests under these conditions and so tests with the

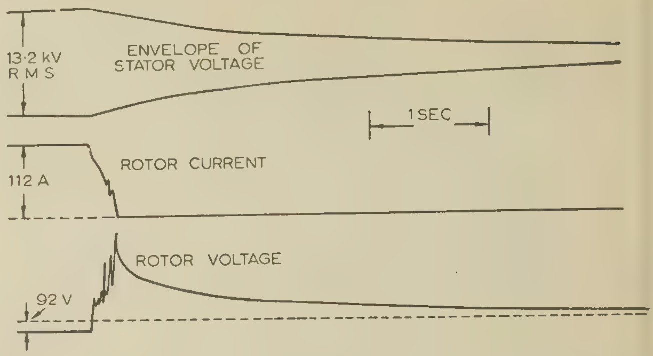

Fig. 7.—Oscillogram of field-suppression test on turbo-alternator on open-circuit.

Machine A excited to rated voltage and with no discharge resistor.

Table 1

Data for Cylindrical-Rotor Machines used during Field Suppression Tests

	Rating				Machine constants					M.C.R. excitation	
	MVA	p.f.	Voltage	Frequency	S.C.R.	x''_d	x'_d	τ''_d	τ'_d	Current	Voltage
			kV	c/s		%	%	sec	sec	amp	volts
A	40·7	0·75	13·2	50	0·61	10	15·5	0·025	0·5	296	320
B	37·5	0·8	11·0	50	0·54	14·2	17·2	0·020	0·335	312	261
C	62·5	0·8	11·0	50	0·63	12·1	18	0·027	0·61	384	366
D	70·6	0·85	13·8	60	0·92	6·4	9·6	0·027	0·5	412	371
E	35·3	0·85	11·0	50	0·59	12·5	19·1	0·037	0·83	400	328
F	75	0·8	11·8	50	0·61	10·5	15·75	0·020	0·57	428	415
G	111	0·9	13·8	50	0·79	25·3	31·9	0·021	0·505	2 450	356

Table 2

Results of Field Suppression Tests on Typical Alternators

Test number	Alternator	Type of test	Stator voltage before test compared with rated voltage	Ratio of discharge resistance to hot field resistance	Time from s.c. to circuit-breaker contacts parting (t_2)	Arc duration (t_3)	Field current				Field voltage			Decay time-constants (after arc extinction)		
							Initial	Peak	Peak/Initial		Initial	Peak	Peak/Initial	Theoretical*	Field d.c. component	Stator a.c. component
									Test	Calculated						
			%		sec	sec	amp	amp			volts	volts	volts	sec	sec	sec
(1)	A	O.C.	100	1·56	—	0·02	112	112	1	—	92	167	1·8	—	2·88	5·0
(2)	A	O.C.	100	∞	—	0·11	112	112	1	—	92	710	7·7	—	2·28	2·7
(3)	A	S.C.	50	1·56	0·16	0·04	50	707	14·1	11·65	38·6	750	19·4	0·294	0·31	0·38
(4)	A	S.C.	50	∞	0·12	0·14	50	710	14·2		38·5	2 720	70·3	0·10	0·21	0·28
(5)	B	S.C.	50	4·06	0·043	0·07	59	565	9·6	13	35·4	780	22	0·146	0·204	0·414
(6)	C	S.C.	50	4·7	0·386	0·074	75·5	600	8·0	9·53	51·5	900	17·5	0·215	0·29	0·339
(7)	C	S.C.	50	4·7	0·120	0·120	75·5	720	9·5		51·5	1 200	23·3	0·215	0·232	0·348
(8)	D	S.C.	40	5·0	0·27	0·046	68	—	—	—	43	1 170	27·2	0·191	0·254	0·314
(9)	D	S.C.	75	5·0	0·254	0·05	133	1 340	10·1	13·7	86	1 560	18·2	0·191	0·208	0·324
(10)	E	S.C.	50	1·0	0·067	0·013	54	570	10·6		32	430	13·4	0·563	0·495	0·645
(11)	E	S.C.	50	3·0	0·067	0·030	54	585	10·8	8·32	32·2	990	30·8	0·356	0·255	0·454
(12)	E	S.C.	50	5·0	0·066	0·035	54	575	10·6		32·2	1 440	44·8	0·288	0·201	0·395
(13)	E	S.C.	100	5·0	0·062	0·079	118	1 250	10·6		70	2 100	30	0·288	0·197	0·39
(14)	F	S.C.	50	0·71	0·242	0·022	73	695	9·5	11·4	50·7	456	9	0·414	0·59	0·67
(15)	F	S.C.	100	0·71	0·228	0·017	165	1 720	10·4		117	770	6·6	0·414	0·47	0·62
(16)	G	S.C.	25	0·88	0·068	0·005	244	1 400	5·74		32·4	135	4·2	0·353	—	0·532
(17)	G	S.C.	25	0·88	0·316	0·003	262	1 400	5·5		35·6	136	3·8	0·353	—	0·533
(18)	G	S.C.	50	0·88	0·063	0·003	486	2 640	5·42	4·48	65	218	3·35	0·353	0·31	0·495
(19)	G	S.C.	50	0·88	0·357	0·004	490	2 690	5·49		65	171	2·63	0·353	0·52	0·585
(20)	G	S.C.	100	0·88	0·312	0·01	1 044	5 760	5·5		133	428	3·1	0·353	0·404	0·53

O.C. = Open-circuit.
S.C. = Short-circuit.

* The values for the short-circuit tests were calculated from the expression $\frac{\tau'_d}{K+1} + \tau_{kld}$, $\frac{\tau_{kld}}{\tau''_d}$ being taken as 4.

alternator excited to voltages up to rated voltage on open-circuit before applying a stator terminal fault were made on the seven machines listed in Table 1. A typical oscillogram obtained during these tests is shown in Fig. 3.

In some of the tests, the tripping of the field circuit-breaker was delayed to enable the machine characteristics to be determined. The transient field current had then decayed considerably by the time the field breaker opened and consequently the duty imposed on that breaker and the over-voltages produced across the field winding are less than those produced with normal tripping times. A further disadvantage is that the magnitudes of the currents after operation of the circuit-breaker are so small that the calculation of the time-constants cannot be determined with any great degree of accuracy. To result in a more arduous duty for the circuit-breaker, in several tests its tripping was initiated so as to give interruption shortly after the fault.

The time-constants were obtained by plotting the varying quantity against time using logarithmic scaled graph paper. The time-constant was then taken as the slope of the graph after the sub-transient components had decayed. In the case of the field currents, the decay was found to be not purely exponential and so the time-constant was taken as the average slope over the first 20 cycles.

It will be seen from Table 2 that the measured time-constant of the decay of armature a.c. component of current is greater than that for the d.c. component of field current. The theoretical value corresponds to τ_α, defined after eqn. (20), and the term τ_{kld} has been given a value $4\tau_d''$ for this purpose. The tests on machine A are of interest since two of these are for field opening with open-circuit conditions on the armature; also, two tests were done with no discharge resistor connected, and these illustrate the high peak rotor voltage reached even on this relatively small machine with no discharge resistor.

Table 2 shows that the calculated peak rotor currents lie within approximately $\pm 25\%$ of the test values. It is considered that the following factors account for this discrepancy:

(*a*) The assumption of constant reactances and absence of saturation is not, in practice, justified.

(*b*) The value of λ in the expression for peak rotor current is directly dependent on the differences between X_d'' and X_l, and between X_d' and X_l. Since X_l constitutes a large part of X_d'' and X_d', small errors or uncertainties in estimating the values have a large effect on λ and therefore on the calculated peak current. X_l cannot be measured alone by direct methods and so there is of necessity considerable uncertainty about the true value of λ.

(*c*) In the calculations it has been assumed that the peak current occurs $1\frac{1}{2}$ cycles after the moment of short-circuit (i.e. t in the expression for current has been put at 0·03 sec). Examination of the oscillograms show this to be approximately but not strictly true. The error resulting from this assumption is small compared with those attributable to factors (*a*) and (*b*).

It is clear that linear machine theory can give only approximately correct values and that the effects of saturation and additional damper paths must be considered in order to achieve better agreement with test results.

(8) THE RATING OF THE DISCHARGE RESISTOR

For the purpose of field suppression the discharge resistor must be capable of carrying the field current of the synchronous machine under conditions of short-circuited stator. This current may have a peak value of up to five times the m.c.r. field current of the machine and a time-constant of decay whose value will depend upon the machine characteristics and the value of the discharge resistance.

Owing to the initially high current and the short time of field suppression, the resistor design is usually based upon its thermal capacity rather than its heat-dissipating capabilities. It is common in the case of all but the very small machines for these resistors to be of the 'grid' type which are suitable for operation with a temperature rise of 265°C. Where they are mounted in the field-suppression cubicle, care must be taken to ensure that, if the resistor temperature reaches this value, it will not result in damage to cables or other equipment.

A suitable rating for such a resistor, having a resistance equal to that of the hot field winding, would be the m.c.r. of the field winding for 10 sec. Increasing the discharge resistance would not reduce the possible maximum value of the current but would reduce the time-constant of the decay of current by the factor $2/(K+1)$ approximately. The heat rating of the resistor is thus increased by the factor $2K/(K+1)$ approximately.

If the machine is to be run asynchronously, it may be necessary for the design of the resistor to be based on its continuous rating, or, as in the case of certain methods of starting synchronous motors, the time rating may need to be increased.

(9) THE CHOICE OF DISCHARGE RESISTANCE AND CIRCUIT-BREAKER

The factors that have to be considered in choosing a discharge resistance and a field circuit-breaker are the possible extent of damage to the stator, the field circuit-breaker arc duration, and the possible over-voltage produced on the field winding during field suppression. These factors have been discussed separately in earlier Sections and it has been shown that it is the last two which determine the choice of circuit-breaker and the maximum value of the discharge resistance.

Whilst the circuit-breaker is arcing, the voltage across the field winding is limited to a value equal to the full voltage that can be developed by the circuit-breaker less the exciter voltage. If this does not exceed the value which may be safely applied to the field, the discharge resistance must be chosen to limit the duration of arcing to say 0·06 sec, as described in Section 3, or to some lower definite arcing time if the circuit-breaker is one which has a low arc voltage (i.e. a small value of M) as illustrated by the curves for $M = 5$, 7·5 and 10 in Fig. 4.

After arc extinction occurs, the voltage produced across the field may increase as described in Section 6. In order to limit this transient recovery voltage to a safe value it may be necessary to reduce the discharge resistance to a value less than that determined by consideration of the circuit-breaker arcing time alone.

Similarly, if the circuit-breaker arc voltage is such that, if allowed to develop fully, it would result in an excessive field voltage even whilst the circuit-breaker was arcing, then the discharge resistance must be sufficiently low to enable the circuit-breaker to interrupt its current before it develops its full voltage, i.e. the arc duration must be limited to a particularly low value.

In practice, with limited choice of field-suppression circuit-breaker, these considerations would usually result in a choice of discharge resistance equal to about 1·5–1·0 times the hot field resistance for alternators between 75 and 300 MVA. For smaller machines it may be permissible to use a discharge resistance up to 5 times the hot field resistance.

Notwithstanding the above, it must be borne in mind that only a very limited number of circuit-breakers are available from which to choose. It would not be economic to have a range of arc chutes for each size of circuit-breaker, the size being based on the required normal current-carrying capacity.

Since the expressions quoted in the paper give only approximate solutions, a safety factor must be allowed when choosing the value of the discharge resistance.

(10) THE TESTING OF THE FIELD-SUPPRESSION CIRCUIT-BREAKER

As explained in Section 7, it is not possible to test the field-suppression circuit-breaker to its maximum required duty in conjunction with the alternator. It is therefore essential to consider the method of testing which should be employed to prove the suitability of the field-suppression breaker.

Making use of the expressions derived in the Appendix it is possible to obtain a reasonable estimate of the conditions under which the breaker is called upon to operate in service. Knowing these conditions, the proving of the circuit-breaker can be carried out separately on its two parts, namely the main-field contacts and the discharge contact.

(10.1) Main-Field Contacts

The current the main contacts are required to make and carry depends only on the exciter voltages and the field winding resistance. There is no difficulty in proving the breaker's ability in this direction.

The problem of synthesizing a test circuit for proving the interrupting ability of the main contacts is, however, a very difficult one. It is impracticable to set up a circuit on a test plant which will reproduce the worst conditions in the field circuit of a synchronous machine under which the breaker is required to operate, as represented by the expressions derived in Section 15. It would be completely uneconomic and departing from standard practice to attempt to set up such a truly equivalent circuit for each synchronous machine design.

Synthetic test circuits where a single circuit represents the field circuit of a synchronous machine under stator fault conditions have been proposed.[1, 2]

One such circuit is shown in Fig. 8. In this, the supply voltage

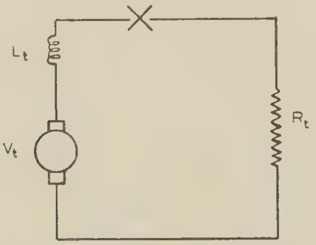

Fig. 8.—A proposed synthetic test circuit for proving the interrupting rating of the main contacts.

V_t is given as $V_e + R_d I_f$, where V_e is the voltage of the exciter at the time of the short-circuit on the machine, R_d is the discharge resistance, and I_f is the mean field current at the instant of field circuit-breaker operation. R_t and L_t are equal to the total resistance and reactance respectively of the exciter and the discharge resistor.

Two important assumptions are made in obtaining this circuit, these having a considerable bearing on the operation of the circuit-breaker.

Using the voltage chosen is equivalent to assuming that the field current remains constant throughout the period when the breaker is arcing. This is only reasonably true if the arcing time is short, and if this is so the breaker will be suitable since it will be working well within its capabilities. To obtain interruption in this synthetic circuit it is essential that the circuit-breaker be capable of producing an arcing voltage at least equal to V_t, and the arcing time will depend on how much this arcing voltage exceeds it.

As seen from the oscillograph of an actual field suppression operation in Fig. 3, while the circuit-breaker is arcing the field current is being reduced by the energy dissipated in the arc chute, in addition to the reduction due to the effect inside the alternator which would have occurred if the field circuit-breaker had not opened. In practice, the conditions for interruption are therefore improving throughout this period.

The second assumption made in proposing such a synthetic circuit is that the a.c. component of field current has no appreciable effect on the operation of the circuit-breaker. It is the authors' experience that, in practice, final interruption occurs at, or very near, a negative peak of the a.c. component of field current. It is possible for interruption to occur at other times, but this necessitates short arcing times and takes place during stage 1 of the interruption, as defined in Section 3, before the arcing voltage reaches its steady full value.

It is the authors' contention that, for the above reasons, it is of little value to use such a simple synthetic circuit for proving the interrupting ability of the main field contacts of the breaker. The arcing times obtained during the test would generally be longer than in practice, and it would still be necessary to determine by other means the true arcing time and the maximum voltage impressed on the field winding.

It is therefore felt that the suitability of the field circuit-breaker main contacts as regards interrupting capacity is best proved by first determining the interrupting characteristics of the circuit-breaker. These characteristics are the rate of rise of the arcing voltage produced by the circuit-breaker, its full steady value, and the permissible arc duration which would not cause serious damage to the circuit-breaker or result in a flashover in the cubicle.

The form and value of these characteristics can be obtained using a simple d.c. test-plant circuit incorporating sufficient inductances to obtain a range of arcing times with the range of currents likely to be encountered in field-suppression duty. The choice of circuit voltage is not critical and different values could be used with one value of inductance to obtain the range of arcing times instead of a series of inductance values.

Having this information available, the performance of the circuit-breaker on any field-suppression duty can be forecast with reasonable accuracy as described elsewhere.

(10.2) The Discharge Contacts

The principal duty of the discharge contact is the making and carrying of the discharge-resistance current during field suppression. The current-carrying capacity should match the rating of the discharge resistance as considered in Section 8. The making-capacity requirement is, however, rather indeterminate since this depends to a large extent on the interrupting characteristics of the main contacts. It is not considered unreasonable to expect the discharge contact to be capable of closing on to the peak field current which is expected at the time the circuit-breaker is operated following a 3-phase stator fault. There is no difficulty in proving this making ability in the usual manner.

If the field breaker is designed so that the discharge contacts open before the main field contacts close, then the discharge contact is not normally called upon to interrupt any current when used on alternators. In fact, few, if any, field-suppression circuit-breakers manufactured in this country up to the present time have discharge contacts designed to interrupt currents.

If, however, the sequence of timing is reversed, then the discharge contact would be called upon to interrupt as a maximum the discharge-resistance current at the exciter ceiling voltage.

The inductance applicable in such a case is that of the cables and the exciter, whose total current will be reduced by that flowing through the discharge resistance. Testing for this condition is straightforward.

'Coarse synchronizing' of alternators has recently been

advocated. In such a case the machine armature is connected to the system before the breaker main-field contacts are closed. Under these conditions an alternating current of slip frequency induced in the field winding flows through the discharge resistance and the discharge contact. The discharge contact therefore has to interrupt this current when the field circuit-breaker is closed. It is not within the scope of the paper to consider this duty in detail but only to draw attention to the trend in requirements.

(11) OTHER FIELD-SUPPRESSION CIRCUITS

Although the field-suppression circuit discussed above is used very extensively, the desire to simplify and cheapen the field-suppression equipment and to increase the rapidity of field suppression has led to the introduction of other methods.

With large alternators (particularly low-speed waterwheel alternators) where the excitation currents are high, it is now quite common practice on the North American continent to suppress the exciter field and allow the alternator field to discharge through the exciter. The heavy copper alternator-field connections are thereby omitted, together with the alternator-field circuit-breaker, and replaced by a smaller and less expensive exciter-field circuit-breaker. This arrangement gives less rapid field suppression, but, since the discharge resistance required with large alternators is usually low, the possible extent of damage to the stator is not greatly increased. Furthermore, the direct-axis transient open-circuit and short-circuit time-constants of large modern turbo-alternators are lower than those of small machines, and this also tends to reduce the extent of stator damage.

Another field-suppression circuit that has been used[3] also allows the alternator field to discharge through the exciter. In this circuit, however, a series resistance is automatically switched into circuit and, at the same time, the full pilot exciter voltage is applied with reversed polarity to the exciter field. A voltage opposing the current flow is thus built up in the exciter. It is claimed that this arrangement gives more rapid field suppression than the usual field-suppression circuit. However, the need to remove the exciter field after suppression has been completed increases the complexity of the circuit.

A further arrangement which has been described[4] uses the original circuit but with a non-linear discharge resistor. As the field is suppressed, the lower current results in a relatively higher resistance and consequently a more rapid suppression of the alternator field. Such a resistor does not reduce the over-voltages likely to be developed across the field winding or have an appreciable effect on the field circuit-breaker arc duration, since it is usual to choose a resistor having a resistance equal to the corresponding linear resistance when passing the field current at the instant of arc extinction in the field circuit-breaker. The advantage gained from the use of a non-linear discharge resistor is that the possible extent of stator damage is reduced slightly.

An arrangement where the field circuit-breaker continues to arc until the field is almost fully suppressed has been described.[5] In this circuit, no discharge resistor is required but the circuit-breaker has to be capable of dissipating its arc energy without damage to itself or causing a flashover within its cubicle. This requires a special design of circuit-breaker which, although proved satisfactory by tests with small alternators, may be impracticable with the larger alternators because of the considerable arc energy that has to be dissipated.

The use of rectifiers to provide the excitation of the alternators enables other forms of field suppression to be used. These have been described in a recent paper by Frey and Noser.[6]

(12) CONCLUSIONS

It is possible from theoretically determined equations based on an ideal machine to make a reasonable forecast of the currents and voltages that will be produced before and during field suppression in the field circuit of a faulted synchronous machine.

It is also possible to use the equations to determine the effect of the value of the discharge resistance upon the extent of damage to the stator resulting from a stator fault. It appears that the relative reduction in total damage is small if the discharge resistance is increased above four to five times the hot field winding resistance. Owing, however, to the induced currents in the rotor body, the decay of stator and rotor currents is not as rapid as is indicated by the equations derived; consequently, the effect of the discharge resistance upon the extent of stator damage is less in practice.

The choice of the discharge resistance is determined either by the permissible arc duration of the field circuit-breaker or by the maximum over-voltage that may be safely applied to the field winding. The rapidity of field suppression could be improved by increasing the insulation of the synchronous machine field circuit and by the use of a circuit-breaker capable of developing a higher arc voltage and arcing for a longer time than circuit-breakers at present used for field suppression. Whether the improvement is justified is a problem in economics.

Other field-suppression circuits are available, but it is doubtful whether the improvement in field suppression justifies the increased complexity of the circuit or whether the equipment is suitable for the high-current excitation of modern large alternators.

(13) ACKNOWLEDGMENTS

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(15) APPENDIX: TRANSIENT ANALYSIS OF FIELD CURRENTS AND FIELD SWITCHING

(15.1) Machine Constants

For the purpose of the illustrative examples mentioned in the paper, values have been given to some of the parameters.

These values are as follows:

$\sigma = 7{\cdot}0$	$\lambda = 0{\cdot}25$
$L = 2{\cdot}91$	$\cos\delta = 0{\cdot}8$
$\tau'_d = 0{\cdot}8$ sec	$\tau_a = 0{\cdot}4$ sec
$t_2 = 0{\cdot}1$ sec	$\tau_B = 0{\cdot}01$ sec

The above figures are representative of turbo-alternators rather than salient-pole machines, but considerable variations from these values are encountered in the whole range of machine ratings. For instance, the armature time-constant, τ_a, may be considerably less than the 0·4 sec chosen here. This affects the amplitude of the oscillatory component in the transient field current and thus also the arcing time calculations which have been illustrated by Fig. 4. Such possible differences must be borne in mind in making use of the examples quoted.

(15.2) Field Current Following Short-Circuit

The differential equations which approximately represent the behaviour of a synchronous machine are derived in numerous references. Adkins[7] describes the calculation of transient field current for a 3-phase short-circuit from rated open-circuit voltage. For a short-circuit from load conditions the major components of the transient field current are given by the following operational expression:

$$I_{fd}(p) = \frac{(1+p\tau_{kd})}{(1+p\tau'_d)(1+p\tau''_d)}\,\frac{p}{p^2+\dfrac{2p}{T_a}+\omega^2}\,\frac{X_{ad}}{X_dR_{fd}}(-\omega V_q + pV_d)1 \quad . \quad (10)$$

The approximate solution to eqn. (10) is

$$I'_{fd} = \sigma\left\{V_q\left[\exp\left(\frac{-t}{\tau'_d}\right) - (1-\lambda)\exp\left(\frac{-t}{\tau''_d}\right) - \lambda\exp\left(\frac{-t}{\tau_a}\right)\cos\omega t\right] + V_d\lambda\exp\left(\frac{-t}{\tau_a}\right)\sin\omega t\right\} \quad . \quad (11)$$

For a short-circuit from rated terminal voltage, V_q and V_d may be replaced by $\cos\delta$ and $\sin\delta$; for open-circuit initial conditions $\delta = 0$. Eqns. (1) and (2) can be obtained by substitution in eqn. (11). The quantity λ can be shown[8] to be given by

$$\frac{x'_d(x''_d - x_l)}{x''_d(x'_d - x_l)}$$

As λ defines the amplitude of the sub-transient and oscillatory components of transient field current, it can be measured from a test record and thus offers a means of evaluating x_l if x'_d and x''_d are calculated from the armature current record.

(15.3) Switching Operations in Field Circuit

The synchronous machine equations lead to the following expressions for the operational impedance, $Z_{fd}(p)$, at the field terminals; the appropriate armature quantities as functions of I_{fd} are also quoted.

Armature phases open-circuited:

$$Z_{fd}(p) = R_{fd}\left[\frac{1+p(\tau_{kd0}+\tau'_{d0})+p^2\tau'_{d0}\tau''_{d0}}{1+p\tau_{kd0}}\right] \quad . \quad (12)$$

$$V_d(p) = I_{fd}(p)\frac{p}{\omega}X_{ad}\frac{(1+p\tau_{kd})}{(1+p\tau_{kd0})} \quad . \quad . \quad . \quad (13)$$

$$V_q(p) = -I_{fd}(p)X_{ad}\frac{(1+p\tau_{kd})}{(1+p\tau_{kd0})} \quad . \quad . \quad . \quad (14)$$

Armature phases short-circuited (assuming no armature resistance):

$$Z_{fd}(p) = R_{fd}\left[\frac{(1+p\tau'_d)(1+p\tau''_d)}{1+p\tau_{kld}}\right]. \quad . \quad . \quad (15)$$

$$I_d(p) = I_{fd}(p)\frac{X_{ad}}{X_d}\frac{(1+p\tau_{kd})}{(1+p\tau_{kld})} \quad . \quad . \quad . \quad (16)$$

When a discharge resistance KR_{fd} is connected across the field winding, the expressions for $Z_{fd}(p)$ must be correspondingly modified as follows.

Armature open-circuited:

$$Z_{fdD}(p) = R_{fd}\frac{K}{K+1}\left[\frac{1+p(\tau_{kd0}+\tau'_{d0})+p^2\tau'_{d0}\tau''_{d0}}{1+p\left(\tau_{kd0}+\dfrac{\tau'_{d0}}{K+1}\right)+p^2\dfrac{\tau'_{d0}\tau''_{d0}}{K+1}}\right] . \quad (17)$$

Armature short-circuited:

$$Z_{fdD}(p) = R_{fd}\frac{K}{K+1}\left[\frac{(1+p\tau'_d)(1+p\tau''_d)}{1+p\left(\tau_{kld}+\dfrac{\tau'_d}{K+1}\right)+p^2\dfrac{\tau'_d\tau''_d}{K+1}}\right] . \quad (18)$$

The total current flowing in the external circuit divides between thc field winding and the discharge resistor in the ratio $KR_{fd} : Z_{fd}(p)$. The above expressions can be considered to represent the impedance associated with voltage or current impressed within the excitation circuit if other impedances in that circuit are neglected. Eqns. (12)–(18) can thus be used to determine the transient field and armature quantities resulting from various field switching operations. Eqn. (18) relates to the condition of greatest interest in this paper and will be rewritten as

$$Z_{fdD}(p) = R_{fd}\frac{K}{K+1}\,\frac{(1+p\tau'_d)(1+p\tau''_d)}{(1+p\tau_\alpha)(1+p\tau_\beta)} \quad . \quad (19)$$

i.e. τ_α and τ_β are the two values given by

$$\frac{1}{2}\left[\frac{\tau'_d+(K+1)\tau_{kld}}{K+1} \pm \sqrt{\left\{\left[\frac{\tau'_d+(K+1)\tau_{kld}}{K+1}\right]^2 - \frac{4\tau'_d\tau''_d}{K+1}\right\}}\right] \quad . \quad . \quad . \quad . \quad (20)$$

For typical values of machine constants,

$$\tau_\alpha \simeq \frac{\tau'_d}{K+1} + \tau_{kld}; \qquad \tau_\beta \simeq \frac{\tau'_d\tau''_d}{\tau'_d+(K+1)\tau_{kld}}$$

If an exponentially rising voltage, $MV_{fd}[1-\exp(-t/\tau_B)]$, is applied to the circuit (neglecting exciter and connection impedances), standard operational methods lead to the following expression for the total current produced:

$$I_B = \frac{M(K+1)}{K}\left[1 - \frac{(\tau_d-\tau_\alpha)(\tau_d-\tau_\beta)}{(\tau'_d-\tau''_d)(\tau'_d-\tau_B)}\exp\left(\frac{-t}{\tau'_d}\right) - \frac{(\tau_\alpha-\tau''_d)(\tau''_d-\tau_\beta)}{(\tau'_d-\tau''_d)(\tau''_d-\tau_B)}\exp\left(\frac{-t}{\tau''_d}\right) - \frac{(\tau_\alpha-\tau_B)(\tau_\beta-\tau_B)}{(\tau'_d-\tau_B)(\tau''_d-\tau_B)}\exp\left(\frac{-t}{\tau_B}\right)\right] \quad . \quad (21)$$

This can be approximated by considering moderate values only for K and by noting that typically, $\tau'_d \gg \tau''_d, \tau_{kld}, \tau_B$. Then $\tau_\alpha \simeq \tau'_d/(K+1)$ and $\tau_\beta \simeq \tau''_d$, so that

$$I_B \simeq \frac{M(K+1)}{K}\left[1 - \frac{K}{K+1}\exp\left(\frac{-t}{\tau'_d}\right) - \frac{1}{K+1}\exp\left(\frac{-t}{\tau_B}\right)\right] \quad . \quad . \quad . \quad . \quad (22)$$

The currents flowing through the field circuit-breaker comprise:

(a) The initial steady-state field current.
(b) The additional transient components of field current.
(c) The current drawn by the discharge resistor from the exciter.
(d) The transient current produced by the field circuit-breaker.

The effective transfer of the field current into the discharge path can be analysed by injecting equal and opposite currents at any appropriate time. In practice, this will usually be when the total of the above components is instantaneously zero. Such a calculation gives an expression for the current subsequently circulating in the field and discharge resistor. The armature currents, the voltage across the field and the recovery voltage across the field circuit-breaker can also be calculated. The complete expressions including all the transient currents are lengthy and will not be quoted here. An idealization of the field circuit-breaker operation can be obtained by considering only the components (a), (b) and (c) above. Further, (b) can be approximated by neglecting the sub-transient and oscillatory terms. Then for a short-circuit from rated open-circuit voltage, and measuring time from an instant t_2 after the short-circuit, the required current injected is

$$I_S(t) = -\frac{V_{fd}}{R_{fd}}\left\{1 + \sigma \exp\left[\frac{-(t_2+t)}{\tau_d'}\right]\frac{1}{K}\right\} \quad . \quad (23)$$

Neglecting the short time-constant terms in $Z_{fd}(p)$ permits it to be approximated as $R_{fd}(1 + p\tau_d')$; the current I_S then divides between the field and discharge resistor in the ratio $K : (1 + p\tau_d')$. The field current thus subsequently contains terms given by

$$-I_S(p)\frac{K}{(1+K)+p\tau_d'}, \text{ or } -I_S(p)\frac{K}{K+1}\,\frac{1}{1+p\tau}$$

$$\text{where } \tau = \tau_d'/(K+1)$$

This can be shown to lead to the final result for the field current, after the ideal transfer to the discharge resistor:

$$I_{fds} = \frac{V_{fd}}{R_{fd}}\left[1 + \sigma \exp\left(\frac{-t_2}{\tau_d'}\right)\right]\exp\left(\frac{-t}{\tau}\right) \quad . \quad (24)$$

The result in this much simplified case, as might be anticipated, is that the instantaneous value of the field current at the moment of suppression decays with time-constant $\tau_d'/(K+1)$. The corresponding change in decay of armature currents can also be shown to result from this operation.

(15.4) Damage at a Stator Fault Point

An approximate measure of the energy dissipated at a fault can be formed by assuming that a constant-voltage arc is associated with each phase current in a symmetrical 3-phase fault. It is then necessary to evaluate $\int |I| dt$ over the whole period during which currents persist. During the first portion of this period, fault current flows from the generator itself and also from the system to which it is connected; when the main circuit-breaker and field circuit-breaker have opened, the remaining current corresponds to the decay of stored magnetic energy, in the presence of whatever discharge resistance may have been connected across the field circuit.

The value of $\int_0^t I \exp\left(\frac{-t}{\tau}\right) \sin \omega t dt$ can be shown to be approximately given by $I\frac{2\tau}{\pi}\left[1 - \exp\left(\frac{-t}{\tau}\right)\right]$. It may be assumed for simplicity that the machine is operating at no-load but connected to an infinite busbar through a transformer of leakage reactance (on the machine rating) of X_t. Also, suppose that at time t_2 following a 3-phase short-circuit, the main and field circuit-breakers both operate and a discharge resistance KR_{fd} is simultaneously connected across the field. Up to time t_2, the transient component of armature current is proportional to $(V\sigma/X_d) \exp\left(\frac{-t}{\tau_d'}\right) \sin \omega t$; there are additional components $V(1/X_d + 1/X_t) \sin \omega t$, corresponding to the steady-state short-circuit current of the machine and to that fed in from the system. After time t_2, the reasoning given at the end of Section 15.3 above enables the value

$$\frac{V}{X_d}\left[1 + \sigma \exp\left(\frac{-t_2}{\tau_d'}\right)\right]\exp\left(\frac{-t}{\tau_\alpha}\right)\sin \omega t$$

to be given to the resulting current. Using the result derived above, the following expression can then be written for the approximate total damage function:

$$D = \frac{V}{X_d}\frac{2\tau_d'}{\pi}\left\{\sigma\left[1 - \exp\left(\frac{-t_2}{\tau_d'}\right)\right] + \frac{t_2}{\tau_d'}\left(1 + \frac{X_d}{X_t}\right) + \frac{1}{K+1}\left[1 + \sigma\exp\left(\frac{-t_2}{\tau_d'}\right)\right]\right\} \quad (25)$$

(15.5) Analytical, Analogue and Numerical Methods

The analytical results quoted in Sections 15.2, 15.3 and 15.4 are useful for the information which they give about the general form of the results to be expected in practice. They also bring out the dependence of amplitudes and time-constants on particular parameters. Limitations arise from the approximations necessary in setting up the original machine equations and also those in obtaining manageable algebraic expressions at various stages in the derivations. The principal divergences from actual machine performance occur in the neglecting of any saturation and the representation of all eddy-current paths by a single winding in each axis.

Analogue circuits have been extensively used to study synchronous machine transient performance for particular examples. The limitations mentioned above can be to some extent overcome by the provision of suitably saturating units and by representing additional windings, if values can be given to the circuit elements for such additions.

Recently, digital computers have also been used to solve the basic synchronous machine equations for particular numerical examples. Standard programmes are available which handle sets of simultaneous differential equations by step-by-step procedures. Any definable non-linearity can be introduced at each step in a completely rigorous way, and the number of additional windings to represent eddy-current paths is limited, as for analogue computers, by the ability to evaluate the constants. It may be expected that digital methods will be increasingly employed in calculation of machine performance, including the operation of field suppression and other topics discussed in the paper.

DISCUSSION BEFORE THE NORTH STAFFORDSHIRE SUB-CENTRE, AT STAFFORD, 16TH NOVEMBER, 1959

Mr. W. W. Holburn: Any attempt to estimate the probable core damage resulting from stator-winding faults is likely to be speculative, as many indeterminate factors influenced by the design of the machine affect the problem. Saturation has a significant effect on stator-current decay time-constants, as shown by the test results in Table 2. For test 5, the figure in the last

column exceeds the corresponding machine transient short-circuit time-constant given in Table 1, although the factor K is over 4 in this instance. The effect of damper circuits is also considerable and lessens the theoretical effect of the discharge resistance on stator fault damage.

It is reasonable to suppose that, in general, core burning is not excessive if a conductor fault in the slot is restricted to a simple insulation failure from one phase to earth, provided that the protective gear operates correctly. The influence of discharge resistance is not critical in such cases, as the fault current is limited by a neutral earthing impedance. This sometimes takes the form of a resistor, selected to match the surge impedance of the generator, and for machines with very large outputs it may be necessary to consider alternative earthing arrangements if the possible earth fault current would otherwise become excessive and so increase the danger of an inter-phase fault.

Would the authors agree that the insistence on rapid field suppression at the expense of high induced voltages cannot be justified by any evidence other than the purely theoretical, and that the discharge resistance should be chosen to protect the field circuit-breaker or the alternator field winding, whichever is the more vulnerable?

Mr. J. Wainwright: Although the authors have kept within the limit set by their title, I would have liked to see more information on the *raison d'être* for the paper, i.e. the subject of damage to stator cores, though this is fortunately an infrequent occurrence.

Since fault damage is largely determined by the neutral earthing impedance, it would have been useful to have information on present trends for the large sets now being installed.

Earthing via a voltage transformer seems to be out of favour now because of the danger of reflections, but it has served well in the past. Some years ago, I examined a stator core following an earth fault which had existed for 16 hours in an old machine employing this type of earthing. There was no damage to either iron or copper and the repair was effected by replacing a single half-coil.

Other examples of this nature and the small amount of published information which is available* show that, contrary to the statement in Section 5.2 of the paper, damage is by no means proportional to the time integral of the fault current. For a given number of ampere-cycles, damage is greater with the higher currents.

Could the authors comment on the use of a neutral circuit-breaker. Although this may be an expensive item it is a certain way of preventing any extension to the initial damage with both earth faults and phase-to-phase faults.

It is suggested in Section 6 that the maximum rotor voltage should not be allowed to exceed 3 kV peak. With a new rotor this is safe enough, but there is always some insulation deterioration with age and it may be very dangerous for a rotor in later life. Can the authors say what rotor voltages have been allowed to develop over the last twenty years? This information will make it possible to decide whether additional risks are being taken with the larger sets of to-day.

Mr. D. B. Corbyn: The paper shows that rapid field suppression reduced the amount of stator fault damage.

The new conceptions for the excitation of large turbo-alternators aim at the ultimate elimination of slip-rings by the use of rotating silicon rectifiers and an exciter alternator all on the shaft of the main alternator. Small machines of this type are already commercially available. In such a machine there can be no circuit-breaker and the rectifier forms an excellent low-resistance permanent discharge path across the rotor so that the rotor current decays at almost the natural time-constant of the rotor. Is this long time-constant likely to give rise to any serious increase in the risk of stator damage?

An intermediate stage, already in restricted use, is to employ a static semiconductor rectifier and an exciter alternator to eliminate the heavy-current commutator of the conventional exciter. If rapid field suppression is required a circuit breaker and discharge resistor must be used with a consequent risk of high arc voltages. From the point of view of the semiconductor rectifier a low arc voltage is preferable, and capacitors may be necessary across the rectifier output to suppress undue voltage rises.

It appears that it is mainly the stored energy in the magnetic field of the exciter alternator and not the stored energy in the rotor field which may damage the rectifier by over-voltage in the absence of proper precautions.

Mr. B. A. Clare: Another method of field suppression uses an inversely-connected metal rectifier in place of the discharge contacts of the field circuit-breaker. The advantages are:

(*a*) Current flows in the discharge circuit as soon as a short-circuit occurs on the stator windings and before the main-field circuit-breaker opens.

(*b*) The arduous duty of the main-field circuit-breaker is reduced.

(*c*) The circuit-breaker needs no discharge contacts, with a consequent decrease in its cost and maintenance.

(*d*) The time-constant of the discharge circuit is decreased resulting in faster field suppression.

(*e*) Metal rectifiers require less maintenance than circuit-breakers.

From the economic point of view, when the manufacture and use of silicon rectifiers becomes more widely established there will be very little difference between the cost of the rectifier and its maintenance and the reduction in the cost of the circuit-breaker due to removal of the discharge contacts and their associated maintenance.

Silicon rectifiers, with their high current-carrying capacity per unit, will be quite small for this purpose especially if their overload characteristics are used to the full, having in mind the small number of times the field-suppression circuit is used and the short duration of each operation.

If extra safety is required, supervisory control of the rectifier circuit can be easily exercised, using the forward current through the rectifier during normal operation and a unidirectional (rectifier) instrument connected across the discharge resistance.

Mr. E. Bolton: The value of the argument relating to core damage and shown in Fig. 6 would have been considerably enhanced if it could have been backed up by some actual figures of the core burning to be expected. If, for example, it could be shown that, with a factor $K = 5$, the core damage would be such as to warrant rebuilding the machine core, there is obviously no difficulty in reducing the discharge resistance to $K = 1$ or less, thereby reducing the over-voltage applied to the rotor and possibly simplifying the field circuit-breaker.

[The authors' reply to the above discussion will be found on p. 155.]

* For example, POHL, R.: *Elektrotechnische Zeitschrift*, 1927, 7, p. 200, and *A.E.G. Mitteilungen*, 1930, 1, p. 36.

DISCUSSION BEFORE THE SUPPLY SECTION, 9TH DECEMBER, 1959

Mr. L. W. James: During the last few years the size of generator units has increased rapidly from an average of 40 to 50 MW with an excitation current of 400 amp, to 350 MW and upwards requiring excitation currents of around 4 kA. Experience of machines requiring excitation currents of thousands of amperes is very limited, since they have been in commission for only a relatively short period.

Some trouble has been experienced with the field switches supplied with small units, and the practice has arisen recently within the C.E.G.B. of installing switches in the exciter-field circuit to trip at the same time and act as a back-up to the main field switch.

The number of stator failures has, however, been very small, and the amount of core burning extremely small, suggesting that field suppression has been satisfactory. Usually with single-earth faults the normal arrangement of neutral earthing limits the fault current to a small value. Occasionally we get phase-to-phase faults in the end windings of machines or the connections to transformers when very large currents can flow, and if we do not suppress the field quickly serious trouble can result.

In Section 5.1 the authors say that the usual practice is to earth the generator through an impedance of some kind. This requires clarification so far as the C.E.G.B. system is concerned. Though there have been a number of experimental installations of various methods of neutral earthing the general practice for some years has been to earth the neutral through a non-inductive resistance to give a current of about 300 amp when full phase voltage is applied. This practice followed a series of unfortunate failures with high-impedance earthed neutrals.

The last paper dealing with field suppression in any detail was that by Kuyser* in 1922. This compared a number of methods and showed that the best, with the size of the machines then in use, was to open-circuit the field. The field switches were so designed that the arc acted as a self-regulating resistance in series with the field winding and exciter armature. Kuyser applied this method to large numbers of machines of up to 100 MW with apparently perfectly satisfactory results, and almost all the machines being installed on the British system ten years ago used it.

It may be of interest to compare an oscillograph record obtained on a 40 MVA machine with Fig. 3. The arcing time of the breaker was 0·3 sec, the peak rotor current, 1·2 kA, and the voltage, 2·2 kV, starting from conditions almost identical with those in Fig. 3. This test with no discharge resistance gave, after 30 cycles, a ratio of current in the stator to initial current of about 70% of that shown in the authors' test, so that in spite of the long arcing time on the breaker there was apparently an improvement in the overall result.

However, very much larger machines were being constructed, and a number of tests carried out by various makers showed that the best compromise, considering the duties on the rotor and on the switch, would be to use a discharge resistance of the order of 4 to 5 times the cold rotor resistance. A resistor of this value was included in the standard specifications produced by the then British Electricity Authority in 1951 for 60 MW machines and was later used for ratings up to 200 MW.

The size of machines continued to increase and a later review suggested that the value of 4 to 5 times was a little high, so that in 1955 it was modified to 3 times the cold rotor resistance, or approximately twice the hot resistance, which is not far from the authors' suggested figure of $1\frac{1}{2}$ to 1. This value has been used from 1955 to the present time.

* Kuyser, J. A.: 'Protective Apparatus for Turbo-Generators', *Journal I.E.E.*, 1922, 60, p. 761.

In Fig. 6, with a change from $K = 2$ to $K = 1$ and taking the ratio t_2/τ_d' as 0·1, the value of D increases by about 27%; while this may not be serious if it occurs inside the stator, we have to consider the safety of smaller apparatus connected directly to the machine terminals—auxiliary transformers and the like—where it is essential to keep the fault energy to a minimum. If we take $K = 0$, which would correspond to a field switch in the exciter circuit only, as used in some recent American installations, the fault energy appears to double.

There appears to be a difference of opinion about how to produce the figure for D. Some of the information which we have obtained suggests that we should use $\int I^2dt$, whereas the authors use $\int Idt$.

Regarding Sections 8 and 10.2, manufacturers generally tell us that we can operate machines at full load without field for periods up to 1 min. Will the proposed design of field-suppression contacts and resistors carry current corresponding to full load for 1 min on asynchronous operation?

Monsieur P. Laurent (*France*): My contribution is limited to the solutions adopted by Électricité de France in its own power stations.

The system described by the authors, which involves a discharge resistor and a field circuit-breaker, is essentially the same as that which we use for waterwheel generators of moderate size, say up to 30 MVA. The discharge resistance is 4 to 5 times the hot field resistance. For turbo-alternators we are not concerned with such small rating and have concentrated on two standard types, namely 125 and 250 MW. For these big machines, the systems, though they differ in detail, are all based on the principle of reversing the exciter field until the flux has reached the extinction point. It is certainly possible, in the case of heavy short-circuits inducing high currents in the field of the alternator, to develop initially higher back voltages with resistors, as in the authors' system, than by simply reversing the exciter field, but the voltage drop in the resistance decreases rapidly with time.

We thus consider it preferable to apply a constant back voltage to do the whole process of flux suppression. This back voltage can be made equal to the exciter maximum voltage. Some manufacturers maintain the exciter back voltage until minimum-voltage relays at the main terminals indicate that the flux approaches zero. These relays on the stator terminals would give a wrong indication in the case of a 3-phase short-circuit, and therefore a time delay is provided between the closing of the relay contacts and the suppression of the negative excitation. This delay is adjusted by test so as to allow the flux to fall approximately to zero after a 3-phase short-circuit.

Other manufacturers simply use a field-current relay. In the case of a waterwheel alternator with laminated poles, the flux approximately follows the decrease of the field current and the relay is set at approximately zero current. With turbo-alternators, however, owing to the induced current in the solid poles the internal flux may retain 60–70% of its initial value when the field current has dropped to zero. In that case the relay is set at a negative value of the field current, which is adjusted by test to correspond to zero voltage at the alternator terminals. These systems can suppress the remanent flux of the alternator, which might maintain voltages of the order of 1 kV at the terminals.

Usually, but not always, the suppression of the negative exciter voltage is accompanied by the closing of the alternator field on a discharge resistor and the opening of the exciter circuit, but the circuit-breaker and the discharge apparatus then have a very light duty. We do not combine the application of a negative exciter voltage with the insertion of a series

resistor in the alternator field circuit. In the case of a phase-to-earth fault the current is limited by a high resistance in the neutral to a maximum of about 30 amp, which is a tenth of the figure quoted by Mr. James.

Mr. D. A. Muret: In Section 10.1, the authors state that the synthetic test circuit is of little value, their objections appearing to be that the circuit is too severe and may result in an over-designed circuit-breaker. I do not think that their alternative approach, which necessitates obtaining all the arcing characteristics of the circuit-breaker and then extrapolating them to forecast its performance in a given circuit, offers any advantages. It will require a d.c. test plant of similar size, and the factor of safety necessary to cover the uncertainties of extrapolation will be no smaller than that introduced by the claimed severity of the synthetic circuit.

I agree with the authors' suggestion that the arcing time of the circuit-breaker should not exceed 60 millisec, and I am surprised that in the only oscillogram which they give the arcing time is nearer 100 millisec. It is also surprising to see the long flat top on the arcing-voltage record. It is true that a d.c. circuit-breaker interrupting a highly inductive circuit will show this type of characteristic, but in this case, with a discharge resistance connected virtually across the circuit-breaker, it is our experience that this gives an operation which corresponds much more closely to the interruption of a resistive current.

The authors touch on the duty on the discharge contacts of a circuit-breaker when coarse synchronizing is employed. There are designs available which have been employed for coarse synchronizing on site which work very satisfactorily. The duty on these contacts is not severe and does not present any great problems.

Mr. C. Ayers: I have developed a slightly different and simplified approach to the problem of arc suppression of turbo-alternators. The thought behind it is not strictly mathematically correct, and it takes a few liberties with the authors' exponential functions. In essence it says that

$$\sigma = \frac{1}{(\text{s.c.r.})X'_d} = I'_{fd}$$

Discharge Resistance $= K$ per unit.

$$I_\alpha = \frac{1}{K}$$

and

$$V_\beta = \sigma K = \frac{K}{(\text{s.c.r.})X'_d}$$

For the authors' machine E, the maximum current according to this simple theory is 8·8, and their figure is 8·3. For machine F the figures are 10·4 and 11·4. and for machine G, 3·96 and 4·48, respectively. Similarly, with voltages, for machine G the maximum voltage according to this simple theory is 3·5, while the authors' figure is 3·1. The theory seems to give a very good approximation, bearing in mind the main machine characteristics—the discharge resistance, the short-circuit ratio and the transient reactance—and it throws light on the relationship between the machine design and discharge resistance. The authors will probably agree that it is within the 25% acccuracy which they claim for their method.

Turning to the field suppression, we know the current that we have to break and the recovery voltage. Why cannot we simply use these values and test the circuit-breaker, rather than test it over a series of figures, get a matrix of the dependence of various parameters, and then virtually guess whether it will do its duty?

Mr. P. T. Thornhill: I am surprised at the extremely small discharge resistances proposed in Section 9, where, for 75 to 300 MVA machines, figures of between 1 and $1\frac{1}{2}$ times the hot field resistance are suggested. The company with which I am associated has made a practice of providing discharge resistances of from $2\frac{1}{2}$ to 4 times the hot field resistance for even the largest machines. When using such values, the over-voltages produced on arc interruption are never in excess of the 1 min test voltage applied to the field winding, but may be such that special designs of field circuit-breaker are required for the high-voltage interrupting duty involved.

An approach to the question of circuit-breaker and discharge resistance selection somewhat different from that described in the paper has also been adopted. The procedure has been to test a range of circuit-breakers on a d.c. test plant to determine, by actual operation, the limits of current and voltage for which the various designs are suitable. The expected currents and voltages appearing in the rotor circuit are calculated under 3-phase stator fault conditions for any particular machine and a suitable discharge resistance is selected to keep them within the proved capabilities of one of the tested circuit-breakers. The calculated voltage is the peak value of the combined a.c. and d.c. components, and the circuit-breaker chosen has been tested at a voltage in excess of this.

The method of assessing the characteristics of field circuit-breakers on a simple d.c. test plant, as described in Section 10.1, is interesting, but I consider that it is preferable to prove the circuit-breaker at the actual voltages and currents met with in practice, even if this necessitates having it tested abroad because of lack of suitable d.c. testing facilities in this country.

Mr. V. Easton: The excitation requirements of an alternator are greatly affected by the specified s.c.r. and power factor and Fig. 2 should be qualified in this respect. Considering values relating to large machines currently projected in this country, namely 0·4 and 0·85, respectively, the excitation power for a 400 MVA unit may be less than 1 500 kW. The higher value of about 2 800 kW shown in the paper is readily acceptable thermally with increased cooling, but it does represent a significant reduction in efficiency.

The rotor maximum direct current as required for synthetic testing of field circuit-breakers may be calculated, assuming that it occurs a few cycles after the fault when the subtransient component has disappeared and the transient component has suffered negligible decrement. Equating stator and rotor m.m.f.'s,

$$\text{Maximum direct current} = \frac{\text{Initial field current}}{\text{s.c.r.} \times \text{transient reactance}}$$

$$= \frac{\text{Rated load field current}}{(1 + 0{\cdot}93\ \text{s.c.r.})X'_d}$$

approximately for 0·85 p.f.

These simple formulae, using well-known constants which can be checked from tests, show that the higher transient reactance of alternators with direct-cooled rotors tends to offset the effect of higher excitation powers. In fact, for the alternator quoted, with a transient reactance of 28%, the maximum direct field current will be only about $2\frac{1}{2}$ times the full-load current. The assumptions made give pessimistic results, i.e. the calculated maximum currents are larger than the test values by 10 to 25%.

For faults on load the actual current will be increased due to the higher generated voltage, but to calculate this using the accepted leakage reactance is again pessimistic since slot leakage flux is merely distortion and the gap flux is increased only by the end-winding leakage flux. The latter represents

approximately 50% of the leakage reactance, and hence the maximum field current for faults on load may be 10% higher than on no-load, which is within the margin inherent in the formulae.

It is doubtful whether saturation has much effect on the discrepancy between the authors' calculated and test results—probably not more than 5%. The test results for machines E and G support this view.

Dr. P. D. Aylett: In Section 5.2 the authors refer to the estimation of core damage—an important issue when deciding what form of field suppression to use—and the curves have been derived for 3-phase faults. This is not representative of the conditions likely to arise in practice; one would not expect to have a 3-phase fault sufficiently near the core to cause damage. The preoccupation of the users with core damage seems exaggerated, and it would be interesting to know how many faults affecting the core have occurred over the past 15 years.

In an earlier paper* tests were recorded in which machines were run asynchronously, and were self-synchronized. In some cases considerable arcing occurred at the field-discharge resistor contacts, arising from the breaking of the slip-frequency currents circulating in the field and discharge resistor when closing the field circuit-breaker. It is not unknown for asynchronous operation to occur in practice, due to the accidental opening of the field circuit-breaker. The ability to reclose the field breaker rapidly and without hazard is most desirable.

It appears that the possibility of core damage is not great and therefore very rapid field suppression is not essential, that field circuit-breakers and discharge-resistor contacts present a hazard, particularly under abnormal conditions, and that the design of suitable field circuit-breakers for very large generators will be difficult. I believe that the best solution is to dispense with both the field discharge resistor and the field circuit-breaker.

The development of new types of high-speed voltage regulators leads to interesting possibilities. These could be designed for rapid suppression with very little additional equipment. They could provide, for example, for exciter reversal without the necessity for reversing switches which appear to be a feature of the French scheme mentioned by M. Laurent. Will the authors comment on such a scheme, which would dispense with both the field circuit-breaker and discharge resistor?

Mr. P. L. Olsen: I do not think that the field-suppression methods used to date have caused any real trouble as far as rotor insulation failures are concerned, and I cannot recall any core damage due to prolonged arcing at a stator-winding fault inside the slot.

In my experience most of the difficulties encountered have been confined to malfunctioning of the field circuit-breaker. The suppression equipment must be specially designed for its duty and it seems wrong to adapt a standard circuit-breaker for the purpose.

The design of field-suppression equipment must obviously be related to the peak field voltage induced and I think that the suppression must be more carefully controlled. This condition cannot always be obtained when interrupting the current with a circuit-breaker.

With regard to the field voltage induced under various conditions, Table 2 shows that, even with infinite discharge resistance, the peak values are well below the test-voltage peaks, and it is suggested that there is no hazard when switching without a discharge resistance. Until about 12 years ago the firm with which I am associated advocated that rotors should be designed to operate with field circuit-breakers not fitted with discharge resistances, but difficulties with the circuit-breakers and other factors led to a change in this policy.

The authors indicate that circuit-breaker and associated equipment are a.c. tested to 2 kV irrespective of the field voltage. In the absence of a British Standard dealing with the equipment it is good practice to specify that all equipment in the excitation circuit shall be a.c. tested to 10 times the c.m.r. excitation voltage of the machine.

With large machines having direct-cooled windings it should not be difficult to design the rotor for high withstand voltages as there is no heat-transfer restriction. With direct-cooled stator windings there is also more freedom in applying insulation, and in the absence of the need to cool externally the windings can be braced more effectively, thus almost eliminating breakdown at slot exits.

Despite these improvements, which make the machine less vulnerable to damage by field suppression effects, alternative means of suppression should be considered for large machines. It should be accomplished without main-field-current interruption and the excitation power should be retained to apply the necessary counteraction. With modern high-speed excitation-control, equipment, suitable methods are available.

Mr. W. Fordham Cooper: Only one speaker has referred to the damage which the short-circuit current may do to unprotected equipment electrically connected direct to the alternator terminals, and in particular, unit transformers and cables to them.

In the past, if the field circuit of the alternator could be immediately opened by inter-tripping, as advocated by Kuyser, there was some hope that the voltage, and thereby the short-circuit current, would be suppressed before the transformer or cables exploded, but it is clear from the paper that the problem of suppressing the field and the short-circuit current is becoming more and more difficult, and in the event of a short-circuit, a unit transformer or other equipment or cables not protected by a circuit-breaker will be blown up. The position has, in fact, radically changed since the time of Kuyser's paper, and I suggest that it is time the practice of connecting unprotected equipment direct to the alternator terminals was reconsidered.

Mr. H. Du V. Ashcroft: Whenever I see an oscillogram such as Fig. 3 I want to see the first part considerably enlarged. The authors explain that the compromise is between the maximum rate of allowing the field to suppress itself and the maximum voltage induced when it does so. I feel that the voltage likely to cause damage is that, at apparently radio frequencies, when the arcing is in process. An advantage of the French system —and a similar scheme has been proposed by Wall*—is that it does not introduce a non-linear resistance into the circuit which allows these transient voltages to build up.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. J. R. Hill, A. H. Hunt, W. J. Joyce and **D. H. Tompsett** (*in reply*): Messrs. Wainwright and Bolton draw attention to a fundamental difficulty: there is very little information on the relationship between the damage done and the magnitude and duration of the fault current. Since, therefore, no definite acceptable limits can be set, the problematical reduction in fault damage attainable by more rapid field suppression must be weighed against the risk of damaging the rotor insulation or, less importantly, the field circuit-breaker itself.

As Messrs. Thornhill and Olsen mention, specially designed circuit-breakers can be used to develop the high arc voltages needed to achieve very rapid suppression. Heavier rotor insulation can be applied to withstand these voltages, but there are

* MASON, T. H., AYLETT, P. D., and BIRCH, F. H.: 'Turbo-Generator Performance under Exceptional Operating Conditions', *Proceedings I.E.E.*, Paper No. 2846 S, January, 1959 (106 A, p. 357).

* WALL, T. F.: 'Large Three-Phase Generators', *Electrical Review*, 1951, 149, p. 437.

economic limits. It must be accepted that field circuit-breaker development is uneconomical, because of the small demand. Extra rotor insulation inevitably reduces the ampere-turn rating of a given rotor, even if direct-cooled conductors are used.

Mr. Thornhill mentions that values of K between $2\frac{1}{2}$ and 4 are used, even for the largest machines, without exceeding the 1 min test voltage (presumably the British Standard 3·5 kV). The rotor and exciter must then be designed for an m.c.r. slip-ring voltage not much above 350 volts, with correspondingly heavy excitation currents. Does this not lead at least to some inconvenience in the design of slip-rings and commutators and in the maintenance of a large number of brushes? We feel that too great a price should not be paid in these directions to obtain so small a reduction in possible damage in the rare event of a stator fault.

Mr. James and Mr. Wainwright query whether $\int Idt$ is a satisfactory measure of the probable damage. With present information, we think it is the fairest available. If we had used $\int I^2dt$, variation of discharge resistance would have had even less effect on the damage function.

Because of the considerations mentioned above, we agree with Mr. Holburn that it is unjustified to incur high rotor voltages in an attempt to achieve very rapid suppression.

Mr. James's review of the circumstances that led to a reduction in the preferred value of K is most interesting. We agree that satisfactory suppression is possible with no discharge resistor for machines up to about 30 MW, but with larger machines it is dangerous to rely on long arcing times since, as Fig. 4 indicates, they may easily become excessive and lead to flashover in the switch cubicle.

M. Laurent's account of the practices adopted by Électricité de France is much appreciated. It would be interesting to compare oscillograms of the exciter-voltage-reversal method with those obtained with circuit-breaker and discharge resistor, and we hope to be able to do this shortly. We shall adopt Dr. Aylett's suggestion that the voltage reversal be done by a.v.r. action.

Several speakers consider that each circuit-breaker should be tested in a d.c. circuit at the current and voltage estimated to occur in service. We agree that such a test is useful to check that the circuit-breaker selected is adequate, but it is first necessary to have tested the range of circuit-breakers, as Mr. Thornhill agrees, to determine their characteristics. We maintain that this can be done adequately and conveniently in an inductive d.c. circuit with a supply voltage lower than the expected arc voltage of the circuit-breaker. Since the paper was prepared we have done tests approaching more nearly to service conditions by using an unsmoothed rectified a.c. supply, and have confirmed the suitability of a circuit-breaker for a 275 MW alternator. With the measurements of characteristics advocated in Section 10.1 of the paper, this gives a full picture of circuit-breaker performance, and not only an assurance that it will clear satisfactorily.

Mr. Ayers's and Mr. Easton's formulae for peak d.c. component are fundamentally not very different from the expression $\sigma = (X_a - X_d')/X_d'$ and would be expected to agree quite closely with the sum of the d.c. and a.c. components as derived in the paper.

Mr. Muret criticizes the performance shown in Fig. 3. This oscillogram was chosen because it better illustrates the stages of the circuit-breaker action on which the mathematical treatment was based than would a trace with very short arcing time.

The rotating-rectifier scheme described by Mr. Corbyn has obvious advantages, and we feel that the impracticability of using a main-field circuit-breaker must be accepted.

Mr. James and Dr. Aylett refer to the behaviour of the discharge contacts; there is no difficulty in designing them, and the discharge resistor, to permit asynchronous operation for 1 min and to allow the circuit-breaker to be reclosed to restore synchronism.

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GENERATOR/MOTOR PROBLEMS IN PUMPED-STORAGE INSTALLATIONS

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SUMMARY

The paper investigates the problems in pumped-storage installations relative to the electrical ratings of the generator/motor units and the possibility of using two-speed synchronous machines for this duty.

In those cases where the set runs in the opposite direction of rotation when pumping to that when generating, the paper discusses the problems arising in connection with starting the set on the pumping cycle, the design of the thrust bearing and the arrangement of the ventilating system.

Frequent stopping is a characteristic of pumped-storage stations, and the paper shows that it is advisable to supplement the action of the friction brakes by a simple form of dynamic braking.

(1) INTRODUCTION

The marked improvement now being obtained in the efficiency of power generation is due mainly to a large increase in the size of turbine-generator units in thermal stations and it will continue in the future as more nuclear stations go into service. These trends demand large capital expenditure, so that, to reap the maximum benefit from this improved efficiency, it is essential that these installations be run for long continuous periods on full load, irrespective of daily and seasonal fluctuations in demand. This requirement can be largely satisfied by operating the thermal or nuclear stations in parallel with pumped-storage stations, in which, during periods of light load on the system, a pump driven by a synchronous motor raises water from a reservoir at the station to one at a higher level. During peak-load periods the water from the higher reservoir is allowed to run back through the pump, now acting as a turbine, which enables the synchronous machine to generate, thus supplying electrical power to the system. In order to achieve minimum capital cost and maximum efficiency, such installations may require units rated at 100–200 MVA.

Although the salient-pole synchronous machines employed in such stations are similar in all their main features to those widely used in hydro-electric generating stations, there are problems relating to size, starting, stopping and reversal of rotation which require special attention in certain aspects of the machine design.

(2) GENERAL

In pumped-storage installations the type of pump-turbine unit is largely determined by the hydraulic head.

(2.1) Separate Pump and Turbine

Where the natural features of the location permit, a high head is always selected, since, for example, a station operating at a head of 1 000 ft costs about two-thirds of one operating at 250 ft.[1–4]

However, at heads above about 600 ft, it is necessary to install a separate pump and turbine coupled in line with the generator/motor. This arrangement is being used in the Ffestiniog installation which operates at a head of 1 000 ft. This double hydraulic unit normally runs in the same direction of rotation for pumping or motoring, so that for either condition the set is started up by admitting water to the turbine casing and synchronizing the electrical machine in the normal way.

If, during generation, the pump remained coupled it would be essential to blow down the pump casing to eliminate the losses resulting from churning the water; even if this were done the small clearance between the pump impeller and the casing would result in excessive heating due to air friction. To eliminate these difficulties it is normal practice to disconnect the pump from the turbine during the generating cycle.[27]

Couplings have been used which permit the pump to be engaged or disengaged without shutting down the unit. A well-known example is the hydraulic coupling, but experience so far seems to indicate that this would not be a satisfactory solution for the large units considered here, particularly on economic grounds.[4, 5] Another arrangement[6] uses a water turbine to run up the pump to speed, the two halves of the coupling being synchronized and engaged automatically. This system has apparently been successful, but considerable additional cost is involved, particularly in the provision of the auxiliary turbine. Such arrangements are designed primarily to avoid the necessity of shutting down the set when changing over from generating to pumping, and vice versa, and to obtain completely automatic operation, thus reducing the change-over time to a minimum. In large units the additional cost and complication of such devices would not be justified by the reduction in time required for the change-over and simpler arrangements are advisable. In one such arrangement the pump is connected at standstill to the turbine by a plain dog coupling.[7] To connect the pump, the set is brought to rest, the pump shaft is rotated by a hydraulic servo-mechanism to the correct position and the coupling is then engaged hydraulically.

(2.2) Combined Pump and Turbine

Owing either to the natural topography of the site or to the selection of a more or less artificial site, e.g. a cliff adjacent to the sea, the available hydraulic head may be only a few hundred feet. In this case the unit may consist of a single turbine/pump unit connected to a generator/motor, resulting in a considerable reduction in the size of the unit and the overall cost of the station. Since the direction of rotation when pumping is necessarily opposite to that for generating, it is not possible to start by admitting water to the turbine. The method of starting on the pumping cycle is thus a problem which requires investigation.

(2.2.1) Two-Speed Synchronous Machine.

A further problem in the use of the combined pump/turbine unit is that, in general, to obtain the maximum pump efficiency, the hydraulic unit should run at about 20% higher speed when pumping than when generating, the gain in pumping efficiency being about 2%. This difficulty could be overcome by installing two electrical machines running at different synchronous speeds, but the increased capital cost would far outweigh the increase in efficiency. Another solution which has been used successfully is the provision of a two-speed synchronous machine.[8, 9] The

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principle underlying the operation of this machine can best be illustrated by considering the simple case of a 10-pole synchronous machine. The fundamental of the flux-density distribution at the stator bore will be as shown in Fig. 1(*a*) and may be represented by the expression

$$B_1 = 1\cdot 0 \sin 5\theta$$

If now the exciting windings on two equidistant poles (poles 5 and 10) are short-circuited and the field current through poles 6,

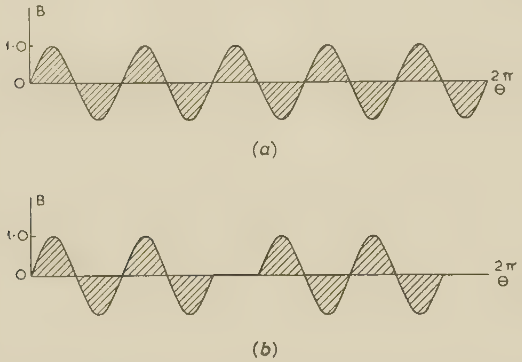

Fig. 1.—Flux density distribution in air-gap of change-pole synchronous machine.

(*a*) Normal 10-pole operation, all field poles in series.
(*b*) Reconnection for 8-pole operation; two equidistant field coils short-circuited and current through half of remaining coils reversed in direction as shown.

7, 8 and 9 is reversed, the flux-density distribution will be as shown in Fig. 1(*b*). Fourier analysis shows that this distribution may be represented by an expression of the form:

$$B_2 = -0\cdot 2 \sin 2\theta + 0\cdot 7 \sin 4\theta + 0\cdot 6 \sin 6\theta - 0\cdot 1 \sin 8\theta + \ldots$$

It can be seen that the original 10-pole wave has vanished and the flux density is now represented by an infinite series of which the two most important terms are those corresponding to 8 poles and 12 poles. Which particular harmonic is used will depend on the actual application, but assuming here that the 8-pole connection corresponds to the pumping cycle, then, since the coefficient of sin 4θ is $0\cdot 7$, there would be a reduction in output of about 30%. This reduction involves an increase in the cost of the electrical machine when compared to that of a single-speed unit, but the increase is of course very much less than that for two separate electrical machines.

There are two methods of designing the stator windings. One is to use a bar winding which, by a designer's *tour de force*, can be made responsive, as required, to either the 10-pole or 8-pole field by a change-over in connections. The complications in design, draughting, manufacture and maintenance, particularly with a large number of poles, e.g. 36/44, are so appalling that this method is best avoided. The method widely used in change-pole induction motors, of providing two entirely separate stator windings, one for each number of poles, was employed on the Flatiron machines,[8] and although this slightly increases the cost and reduces the efficiency, it is much to be preferred on grounds of simplicity to the single-winding arrangement.

The pole change on the stator and rotor can be carried out by links or switches, the former being preferable for low cost and the latter for speed of change-over.

There is a further serious objection to the use of 2-speed synchronous machines of the size being considered here. An examination of the equation for B_2 shows that, in addition to the harmonic which is providing the alternative number of poles, there is a substantial 4-pole harmonic. The pole pitch of this harmonic is twice that of the main harmonic, and it has been shown elsewhere[10] that the core and frame deflection, and therefore the vibration, vary approximately as the cube of the pole pitch. With a large number of poles, e.g. 36/44, this situation is worsened since the pole pitch of the lowest harmonic may be many times greater than that of the main harmonic. Even a low amplitude (e.g. $<0\cdot 05$) of the harmonic could require a very stiff core and frame to avoid excessive vibration. These difficulties have apparently been overcome in the relatively small sets (below 25 MVA) which have so far been built, but, as is well known, the extent to which core and frame vibration may be excessive is difficult to calculate with accuracy, and in the absence of test data on similar size machines—at the moment completely lacking—it is doubtful whether any manufacturer would be so bold as to undertake the design and manufacture of 100–200 MVA change-pole synchronous machines.[11]

However, if such a set could be built to give satisfactory operation, from an economic point of view its use could be justified.

The increased cost of a 2-speed unit rated at 200 MVA 150 r.p.m. would probably be about £200 000. If the capitalized value of a kilowatt is assumed to be £80, the increased efficiency of the pump, say 2%, would result in a capital gain of £300 000, so that the overall gain by the use of a 2-speed unit would be £100 000. There would be a small reduction in this gain due to the lower efficiency of the 2-speed unit.

(3) SIZE OF UNITS

There are no pumped-storage and few normal hydro-electric units with ratings in excess of 100 MVA; in order, however, to achieve the minimum capital cost with the highest operating efficiency, ratings up to about 200 MVA are now being considered. There are two main problems here relative to the mechanical and electrical design.

It is well known that the maximum size of unit which can be built with normal techniques and materials varies, in general, inversely with the speed of rotation, as shown in Fig. 2. The

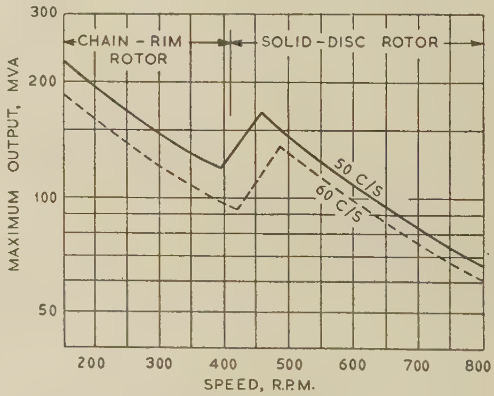

Fig. 2.—Maximum output of large waterwheel alternators as a function of speed.

Overspeed, 80% above normal speed.
Core-length/pole-pitch, 4.
Maximum stress in rotor at overspeed, 30 000 lb/in².
Maximum depth of chain rim, 30 in.
Temperature rise of windings at rated load, 60° C.

solid-disc rotor is essential for maximum-output machines at speeds of about 428 r.p.m. and above owing to the high mechanical stresses involved. Below this speed the chain- or laminated-rim type is used, since it can be designed to withstand the stresses at lower speeds and is substantially cheaper to manufacture than the solid-disc type.[12, 13] The position of the dip in the curve is due to the limitations, imposed by manufacture and transport, on the maximum diameter of the rotor discs.

It can be seen from Fig. 2 that, with the solid-disc rotor, outputs ranging from 100–150 MVA can be obtained over the

speed range of 600–428 r.p.m., while with the chain-rim rotor outputs in excess of 200 MVA are practicable with normal construction at speeds below 200 r.p.m. Thus, provided the factors of speed and overspeed are taken into account, units of 200 MVA and above are well within present-day design and manufacturing techniques.

(4) STARTING (COMBINED PUMP/TURBINE UNIT)

With a combined pump/turbine hydraulic runner, the direction of rotation of the set must be reversed for pumping, and, as already stated, it is not possible to start the set on the pumping cycle by operating the runner as a turbine. It is thus necessary to consider alternative methods of starting the unit for the pumping cycle.

(5) ELECTRICAL STARTING OF UNIT

In order to make this discussion realistic, numerical values are given here which are typical for a waterwheel alternator of the following rating:

210 MVA, 0·95 power factor, 15 400 volts, 3 phase, 50 c/s.
150 r.p.m., 40 pole.
H (inertia constant) = 3·5
Overspeed = 1·6 × Rated speed.
Short-circuit ratio = 1·0
Rating as in B.S. 2613 for Class B insulation.

The simple equivalent circuit of the machine, required in the calculation of the approximate characteristics for induction-motor starting, is shown in Fig. 3.

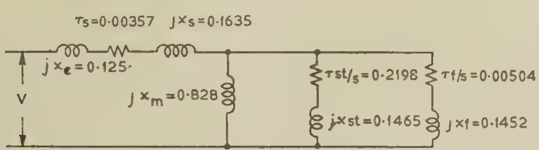

Fig. 3.—Simple equivalent circuit of alternator considered as a squirrel-cage induction motor.
All values are per unit, related to 210 MVA.

The value of r_{st} (0·22), found by trial, gives the maximum starting torque with the other, normal, circuit parameters. In order to avoid high induced voltages in the field winding at starting, it is short-circuited through the field-discharge resistor, the ohmic value of the latter being five times that of the field winding.

With this method of starting and an inertia constant of 3·5, the squirrel-cage winding and field circuit must dissipate $200\,000 \times 3{\cdot}5/0{\cdot}95 = 0{\cdot}735 \times 10^6$ kW-sec between standstill and synchronism.

As can be seen from Fig. 4, about one-seventh of the total energy ($0{\cdot}1 \times 10^6$ kW-sec) would be dissipated in the discharge resistor and there would be no difficulty in designing the resistor for this duty (Fig. 5). In designing the squirrel-cage winding to dissipate the remaining energy the following points require consideration. On the assumption that no heat is dissipated from the squirrel-cage winding during the run-up period, a pessimistic assumption, and that the temperature rise, T, of the winding does not exceed 300° C at the end of the starting period, then the weight of material in the squirrel cage is given by:

$$m = \frac{H \times \text{kVA} \times 10^3}{T \times 4{\cdot}18 \times 453{\cdot}6 \times c_h}\ \text{lb}$$

where c_h = Specific heat of material of winding. Taking $c_h = 0{\cdot}09$ for brass or copper,

$$m = \frac{3{\cdot}5 \times 210\,000 \times 10^3 \times 6}{300 \times 4{\cdot}18 \times 453{\cdot}6 \times 0{\cdot}09 \times 7} = 12\,320\ \text{lb}$$

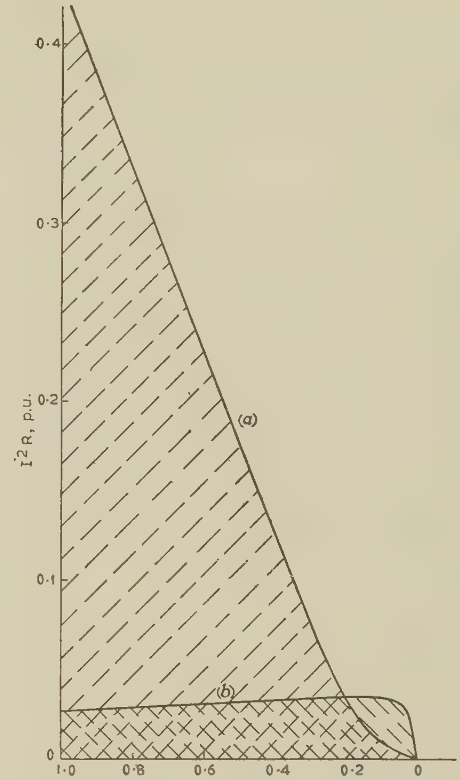

Fig. 4.—Energy dissipated during induction motor starting.
(*a*) In squirrel-cage winding.
(*b*) In main-field discharge resistance.

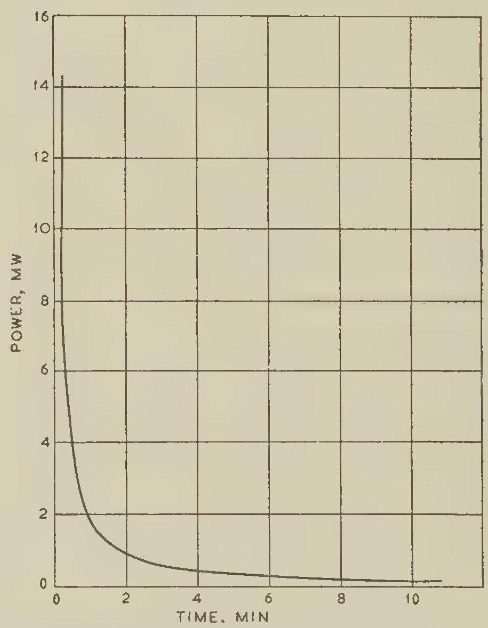

Fig. 5.—Rating of main-field discharge resistance as a function of starting time.

This is considerably more than double the weight which would be used if the winding were for damping only. In addition, complete short-circuiting rings would be required at each end of the winding; these rings, in view of the overspeed, would

have to be supported at the interpolar spaces from the rotor discs or the rim.

If copper were used for the winding, the resistance would be lower than the required value specified in Fig. 3. It is necessary, therefore, to use one of the well-known high-resistance alloys in order to obtain both the specified resistance and the weight.

(5.1) Direct-on-Line Starting on the H.V. Side[14,15]

This method of starting requires no special apparatus and is therefore attractive from the point of view of both capital cost and simplicity of operation. The main objection to the method is that the relatively heavy current drawn from the line during starting may cause impermissible voltage drops from the point of view of local supplies. However, in the case of the large units considered here, the most economical solution is the provision of a spur line connected to the Grid, from which no local supplies are taken; the line and associated generator/motor transformer need then be considered only as reactances in series with the electrical unit during the starting period. A further favourable factor in a station containing several sets would be the fact that after the first set had been run up and synchronized, subsequent sets would draw some of their starting current from sets already running on the bars, thus relieving the line and the Grid of some of the starting load.

On the assumption that the high voltage is constant at the point from which the spur line takes its supply, the variation of starting kVA, torque and time with transmission-line plus transformer reactances would be as shown in Fig. 6. From this it can be seen that with a line plus transformer reactance of 15%, the starting kVA will be about 2½ times rated kVA with a starting torque of 18% of full-load torque, the starting

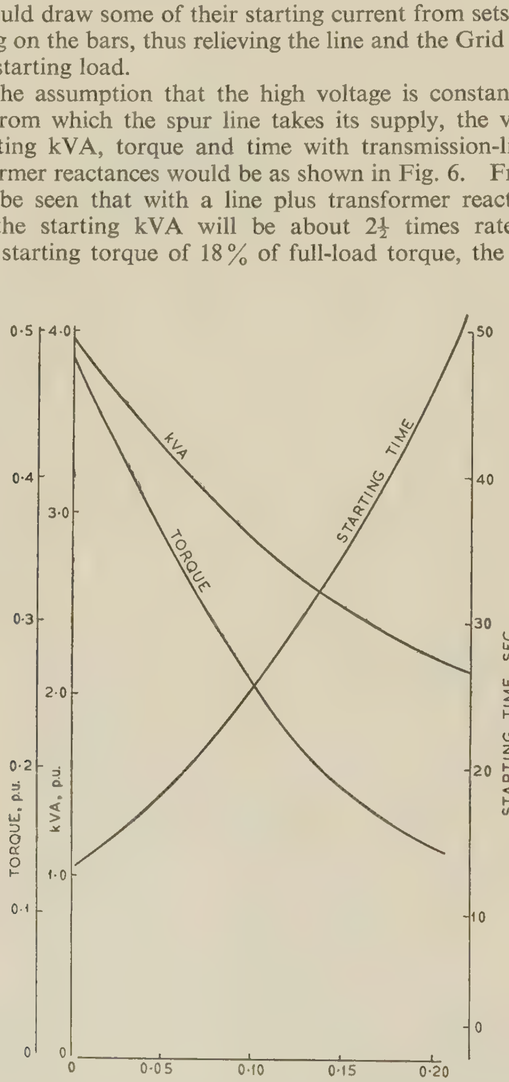

Fig. 6.—Direct-on-line starting characteristics of generator, considered as a squirrel-cage induction motor, as functions of main transformer and transmission line reactances.

time being about 35 seconds. This starting time assumes that the scroll casing is blown during starting; if this were not done, the starting time would be substantially increased and the heat capacity of the squirrel-cage winding would have to be raised. In the recently developed Deriaz turbine/pump runner no churning takes place and blowing down is unnecessary.[16, 17]

The starting current on the 275 kV side would be about 1 100 amp, which is within the capacity of normal 275 kV circuit-breakers. The value of breakaway torque (about 0·18 p.u.) is, as will be shown later, ample relative to the thrust-bearing characteristics.

Objections have been made to the direct-on-line starting of large units in pumped-storage stations on the grounds that the mechanical shock of frequent starting would have deleterious effects on the stator windings. That this would not be so can be seen from a consideration of the following factors.

In general, the stresses set up in an end-winding are a function of the pole pitch, and, as emphasized in connection with Fig. 2, the machines considered here, although of large size, are of normal construction; the pole pitches will therefore usually not exceed about 30 in. There are of course many synchronous motors of comparable pole pitch in operation in this country and abroad which are started frequently, even daily, by direct-on-line starting. It is thus reasonable to assume that no deleterious effects need be anticipated from this cause in the large machines considered here. Nevertheless these factors, in conjunction with the relatively high voltages of 15–18·5 kV at which they would operate, would involve some additional bracing and blocking of the end-windings.

The daily starting and stopping of the unit also raises the question of differential expansion effects in the slot portion of the stator bars. These effects are naturally most marked in machines with long cores of 150 in or more, so that in the normal hydro-electric machine with core lengths rarely in excess of 100 in (the 210 MVA 150 r.p.m. machine considered in the paper would have a core length of about 90 in), trouble from this cause is unlikely. Nevertheless, special techniques have been developed for large hydro-electric generators and high-speed motors to reduce these differential expansion effects to a minimum. These include the design of the turn and main insulation, the correct tolerancing and inspection of the finished bars coupled with special techniques in core building so that the widths of the stator slots provide a snug fit for the stator bars without the use of side packers. This ensures that the bars are neither so tight as to inhibit any movement nor so loose as to render the corona shield ineffectual.

At the instant of closing the machine and transformer on to the line a transient-current surge occurs. Expressed as a symmetrical r.m.s. current, this surge would only be slightly greater than the steady starting current, and its effects, as in the case of large motors with direct-on-line starting, would not be significant.

For the pumping cycle, the main sets are run up with the opposite direction of rotation to that for generation so that provision must be made for reversing the direction of phase rotation. This can be done by sectionalizing the 275 kV busbars and connecting the two sections by isolators.[11] Two of the isolators could then be changed over at standstill to reverse the relative directions of phase rotation of the two sections of the busbars.

(5.2) Direct-on-Line Starting on the L.V. Side

The conditions of starting here are generally similar to those in the previous Section.

The highest voltage for which the machine can economically be wound is about 18·5 kV so that the starting current to

be handled by the 18·5kV circuit breaker would be 1 100 × 275/18·5 = 16 400 amp. This is much higher than the rating of any available circuit-breakers so that this method of starting must be regarded as impracticable.

(5.3) Reactor in Neutral of H.V. Side of the Main Transformer

This is, in effect, a simple method for increasing the reactance of the main transformer during the starting period.

For instance, referring to Fig. 6, with a transformer plus line reactance of 10% the starting kVA could be reduced from 2·84 p.u. without a reactor to 2·2 p.u. by connecting a 10% reactor in the neutral of the transformer, a reduction of over 22% in the starting current. The starting time would be increased to about 48 sec, whilst the torque would fall to about 0·14 p.u., which would still be an acceptable figure.

When the main set reached synchronism the reactor would be short-circuited out by a relatively inexpensive circuit-breaker since both reactor and circuit-breaker, situated as they are at the neutral, would only need to be insulated for 10% of 275 kV, i.e. 27·5 kV.

(5.4) Starting with Reduced Voltage at Machine Terminals

(5.4.1) Tappings on L.V. Side of Main Transformer.

The starting characteristics of the electrical machine, with a transmission-line plus transformer reactance of 15%, are shown as a function of the applied voltage in Fig. 7. As shown later,

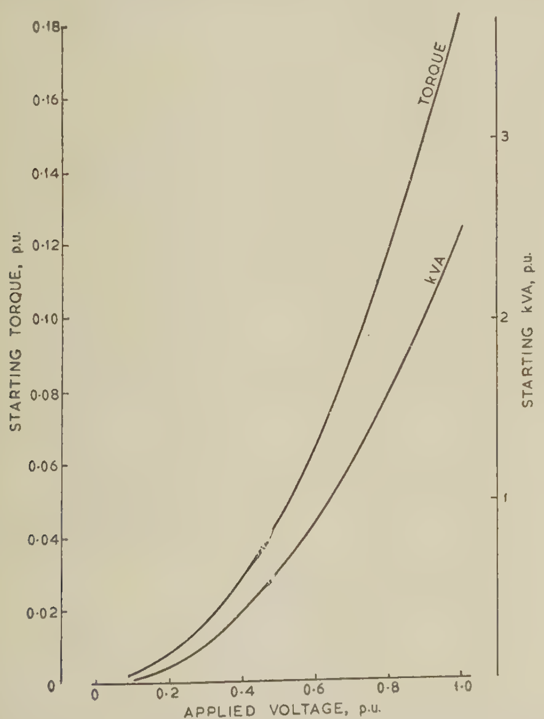

Fig. 7.—Starting characteristics of generator, considered as a squirrel-cage induction motor, as functions of voltage applied to the machine terminals.

Transmission line + transformer reactance = 15%.

the maximum starting torque required is about 0·1 p.u., whilst with special lubricating arrangements this figure can be reduced to less than 0·01 p.u. Assuming, therefore, a figure of 0·02 p.u. starting torque, it can be seen from Fig. 7 that the applied voltage can be reduced to 33% of rated value giving a starting kVA of about 0·23 p.u. with a starting time of about 4½ min. The starting kVA of 0·23 × rated kVA given by this tap would correspond, with a rated machine voltage of 18·5 kV, to a current of about 4 500 amp. This current is outside the capacity of normal circuit-breakers and some development work would be necessary to produce suitable breakers. If the starting time of 4½ min were considered excessive it could be decreased by increasing the percentage tap at the expense of a probably impermissible increase in the required current capacity of the circuit-breaker. As before, these starting times assume that the turbine casing is blown down.

With this method of starting, excitation is applied to the rotor and the machine synchronized whilst still running on the tap. The machine is then disconnected from the tap terminal and connected to the line terminals, and during this so-called 'open transition' the machine may lose synchronism causing a heavy current surge when closing on the line terminal. In the normal case where the low-voltage side of the transformer is delta connected and the tap is 50%, the rotor must slip back 60° between running on the tap and running on the line. It is thus possible by careful timing of the breaker to close on the line terminal when the rotor has slipped back 60°, thus eliminating the possibility of the transition surge. The angle of 60° is valid only for a 50% tap and will decrease with increasing values of the tap. Taps of less than 50% are of course not possible.

In view of the low retarding torque relative to the inertia of the rotor, there would in other cases be little danger of an appreciable surge, particularly if a high-speed circuit-breaker were used to transfer from tap to line.

(5.4.2) Auto-Transformer Starting on the L.V. Side.

This method is in the main similar to that described in the previous paragraph. The chief difference lies in the synchronizing operation, which, with the Korndorfer connection, eliminates the open transition referred to above. The cost of this auto-transformer would, however, be considerably greater than that of providing taps on the main transformer. The apparatus would also take up additional space in the station. As before, circuit-breakers would have to be developed to handle the currents involved.

(5.4.3) Synchronous Starting.[18, 19, 20]

Assuming there are two or more sets in the station, e.g. four, then two or three of the sets are started up as motors, the supply being obtained from the fourth set. With all four sets at standstill, the two or more armatures are connected together and rather less than full-load field current is applied to the machines. The gates are then opened on the set acting as a generator, and the machines accelerated in synchronism up to synchronous speed. The motoring machines are then synchronized with the incoming supply and as before duplicate busbars would be required for this purpose. A condition to be observed with this method of starting is that the combined armature resistance of the motors in parallel, together with that of the generator armature in series, shall not exceed about 0·01 p.u.

The fourth set, which has been used as a generator, is disconnected from the motors, shut down, and then started up in the correct direction of rotation in synchronism by an auxiliary hydro-turbine alternator set running at the highest practicable speed and rated at about 3 000 kW to give a starting time of about 4 min.

With this method of starting there is no line voltage drop and no heavy current inrush in the stator windings; only light damping grids, without rings, are required in the rotor pole faces.

These advantages are obtained at the expense of the substantial additional cost and space requirement of the auxiliary turbo-generator set, and further, this method uses water at a time when the reservoir may have been drawn down to near the minimum intake level.

An alternative which eliminates the auxiliary set is to start the fourth set by direct-on-line starting. The voltage drop would not be serious, since most of the starting kVA would be supplied from the sets already connected to the bars. As against this, all sets in the station would have to be designed for direct-on-line starting, as indicated in Section 5.

(6) OTHER METHODS OF STARTING

There are obviously a number of other methods of starting, such as the provision of an a.c. starting motor on the main shaft or starting by means of a d.c. motor or oversize exciter involving the provision of a large external source of d.c. power; a separate turbine or one combined with the main turbine could also be used. Theoretically starting could also be effected by taps on the high-voltage side of the main transformer. However, an examination shows that for main sets of the size considered here none of these alternatives is a really practical proposition from the standpoints of cost and space required. They will not, therefore, be considered further.

(7) DESIGN OF THRUST BEARINGS[21,22]

Both with the separate turbine and pump and the combined pump/turbine unit it is necessary for the bearing to be suitable for either direction of rotation. In the former case it is necessary to take care of an emergency runaway due to a failure of the supply when the set is on the pumping cycle;[26] in the latter case as a normal running condition during the pumping cycle.

There are three main types of thrust bearing to be considered, the Michell, the Kingsbury and the spring-supported. The Michell and Kingsbury bearings differ only in that the former has a line-contact pivot and the latter a point-contact pivot; in the spring-supported type, the pad is supported by a number of more or less uniformly distributed helical springs which allow the pad to tilt. When required for one direction of rotation only it is common practice in the Michell and Kingsbury bearings to arrange the pivot behind the geometrical centre of the pad in order to obtain the optimum thickness of oil film. A similar result is obtained in the spring-supported bearing by adjustments to the relative degree of spring support at the leading and trailing edges of the pads.

With an approximately square pad, if the centre of support is 0·58 of the tangential length of the pad behind the leading edge, the tilt of the pad, i.e. the ratio of the thicknesses of the oil film at the entry and exit edges, has what experience has shown to be the ideal value of 2·0. Experience has also shown that with a square pad and a tilt of 2·0 a reasonable figure for the minimum oil film thickness is 0·002 in. Lower figures which reduce the friction losses can be tolerated if a finish on the friction surfaces is obtained to an accuracy of a few micro-inches. However, this reduction is obtained with an increase in the cost of the bearing and an increased possibility of wiping at starting after a prolonged standing period, since in a given period there will be less oil remaining between surfaces with a fine finish than between those less finely finished.

A further problem arises here in connection with the stopping and starting duty. During normal running some slight distortion of the pads and supports is bound to take place due to temperature effects, and this slight distortion is easily taken care of by the given thickness of the oil film. If, after continuous running, the set is shut down and then started up again before the bearing is cold, with the very thin film of hot oil existing at starting this distortion cannot be taken up by the oil film and wiping may result.

In hydro-electric generating stations the stopping and starting of large units is usually infrequent. In bearings with natural lubrication it is generally accepted that the permissible specific pressure on the pads is determined by the necessity of avoiding wiping at starting and stopping, particularly the former. After a prolonged period at rest the lubricating film tends to be forced out, and at starting it is not completely re-established until the rotor has made about one revolution.

The rotor of the 200 MW 150 r.p.m. machine considered here, together with the hydraulic runner and thrust, would produce a load on the bearing of 1 100 tons. For unidirectional rotation with pad supports offset as given above and a minimum oil film thickness of 0·002 in corresponding to a specific pressure of 400 lb/in^2, the thrust bearing would produce a loss of about 150 kW.

If now this bearing is run in the opposite direction of rotation, owing to the offset of the pad support an adequate oil film may not be formed. To overcome this difficulty, the point of support is arranged at the centre of the pad so that the pad will tilt with either direction of rotation.

In theory such a pad will not tilt in either direction of rotation and a film would not be formed. In practice, owing to external effects such as the provision of chamfers at the leading and trailing edges of the pads, the pads will tilt, but the minimum film thickness will be less than that permissible from the practical considerations given above; in practice this tilt is found to be about $1\frac{1}{2}$, as previously defined. To restore the minimum thickness of the film to the acceptable value, the specific loading on the pads is reduced to 300 lb/in^2 by increasing the size of the bearing. The value of loss for this bearing, calculated as in the previous case from hydrodynamical theory, is 195 kW, a fairly substantial increase on the previous value. In addition, tests on a range of bearings have shown that the losses with a centre-tilting pad are about 40% greater than those given by theory, so that the figure of 195 kW now becomes 270 kW. This increase in the bearing losses from 150 kW to 270 kW in order to permit rotation in either direction is a serious matter in a pumped-storage station where efficiency is a vital consideration, since the capitalized value of a kilowatt may be as high as £80. This additional increase with the centre-tilting pad makes it important to adopt measures to reduce these losses, not only because of their effect on the machine efficiency but also because they require an increase in the ratings of oil and cooling-water pump motors with additional increases in the losses and costs. This arrangement has the further disadvantage that, since the inside diameter of the bearing is fixed by the shaft diameter, the reduction in unit pressure can be obtained only by increasing the outside diameter by about 1 ft. The corresponding increase in the diameter of the bearing tank may cause transport difficulties, since this tank, being made as a single part, is often close to the limit of the railway loading gauge.

One method of reducing these losses and the diameter of the bearing is to provide high-pressure lubrication to the pads during the starting period.[11, 21, 23] One or more holes are drilled in each pad, and oil from a pump operating at several thousand pounds per square inch is delivered through flexible piping to each pad. The pump is automatically switched on before starting and is arranged to produce the minimum required thickness of film (approx. 0·0025 in) after a brief interval. The set is then started, the pump being automatically switched off at about 20% speed. With this method of starting the minimum thickness of the oil film during normal running can be made to correspond to the lower figure, based on experience, of 0·0015 in. With this thickness of film, the specific pressure on the pads can be increased to 600 lb/in^2 and the resulting bearing will have substantially the same dimensions and theoretical loss of the unidirectional one. However, as stated, this theoretical loss has to be increased by 40% to allow for the central pivot, thus giving

figure of 210 kW. This shows a saving of 60 kW when compared with the figure of 270 kW obtained with a central-pivoted pad bearing without pressure lubrication. The capitalized value of this reduction, say £4 500, is much in excess of the additional cost of the pressure lubrication, particularly as the latter is partially offset by the reduction in dimensions of the bearing by pressure lubrication.

An alternative method of establishing the oil film is to lift the rotor about ¼ in on its jacks and then to lower it back on its pads before each starting operation.[19] Although this method is simple and requires only additional switches and interlocks, it adds several minutes to the starting time, which may be a disadvantage in pumped-storage installations where starting times of 3 min or less may be required. Further, if owing to a leak in the turbine gates the brakes are unable to hold the rotor stationary, then with natural lubrication the resultant crawling may cause the bearing to wipe. With forced lubrication the high-pressure oil pump will come into operation automatically.

A factor in deciding whether the establishment of an oil film prior to starting is important concerns the starting torque. With natural lubrication it is known that the breakaway torque required with large vertical machines is about 8% of full-load torque.[20] Now, if tap starting is used, the lowest permissible tap, and thus the lowest inrush kVA, is determined by the breakaway torque. A reference to Fig. 7 shows that with a breakaway torque of 8% a tap of about 65% would be required with rather more than rated kVA drawn from the line. If the film is established before starting the breakaway torque falls to 1% or less of full-load torque and the choice of tap will then be determined by the permissible starting time.

(8) DESIGN OF BRAKING SYSTEM

In hydro-electric stations with large units, shutting down may be relatively infrequent; in such cases it is sometimes specified that the brakes shall perform 200 operations without renewal of the pads, the corresponding maximum temperature rise being 200° C. Pumped storage may require frequent shutting down, e.g. several times a week, and in these cases steps must be taken to prevent excessive wear of the shoes, since otherwise there is the disadvantage of undue outage time for replacements and the possibility of an excessive accumulation of dust, containing fine metallic particles, on the windings.

There appear to be no reliable data available concerning the wear of shoes owing largely to the fact that the wear is dependent not only on the energy absorbed during braking but also on the temperature of the friction surfaces, which may, because of local heating, approach the charring temperature, about 400° C, of the friction material. The obvious step here is, in the first place, to select a friction material with a high resistance to abrasion and temperature, the metallic content not being too high in order to avoid the excessive deposit of fine conducting particles on the winding. A second step is to install some form of dynamic braking in order to supplement the action of the brakes, although, obviously, at crawling speeds only the brakes can be effective in bringing the set to standstill.

One form of dynamic braking[24] is effected quite simply by short-circuiting and earthing the line terminals of the stator immediately after it has been tripped off the bars, the short-circuit being made by a normal isolator. The rotor circuit is then transferred to a separate d.c. supply and excitation is maintained down to standstill. Apart from the provision of a separate source of d.c. power, the main limitation on this method is the necessity of ensuring that the stator current during braking does not lead to excessive heating of the windings, particularly as braking will usually follow a continuous full-load run.

Typical braking characteristics for the 200 MVA unit considered here are shown in Table 1. The second column gives the various retarding torques additional to the friction brake. The fifth column shows the relative brake wear based on the assumption that the wear is directly proportional to the energy dissipated at the friction surface; with no water or dynamic braking the energy dissipated in the friction pads in bringing the set to rest with the brakes applied at full speed is thus represented by 1·0. The last column refers to dynamic braking and is based on full-load current flowing in the stator winding during the period required to bring the set to rest. These temperature rises will normally be additional to the full-load temperature rise and may therefore be considered to be too high even for the short periods involved. In this case the stator current could be

Table 1

BRAKING CHARACTERISTICS. $H = 3{\cdot}5$

Item number	Additional retardation due to:	Brakes applied at % rated speed	Stopping time	Relative brake pad wear (approx.)	Additional temperature rise of stator winding
		%	min		deg C
1	Friction and windage	100	7·4	1·0	—
		50	14·6	0·28	—
		25	20·9	0·08	—
		0	32·2	0	—
2	Friction and windage, water in casing	100	4·1	0·39	—
		50	4·6	0·19	—
		25	5·4	0·07	—
		0	11·9	0	—
3	Friction and windage, dynamic braking	100	4·6	0·71	25·9
		50	7·4	0·16	41·6
		25	8·5	0·03	47·7
		0	8·9	0	50·5
4	Friction and windage, dynamic braking, and water in casing	100	2·4	0·30	13·6
		50	2·6	0·12	14·7
		25	3·0	0·03	17·0
		0	3·3	0	18·7

reduced to 75% of the rated value, thus reducing the temperature rise by about 25% with a slight increase in the braking time and friction-pad wear. A study of the Table shows that with the normal condition of the casing full and with the brakes applied at 25% speed, the use of simple dynamic braking reduces the relative brake wear from 0·07 to 0·03 with a decrease in the stopping time from 5·4 min to 3·0 min.

In one pumped-storage station with horizontal sets, no mechanical or dynamic braking is used, the run-down time being about half an hour. In the large vertical sets considered here brakes are essential, since with a defect in the thrust bearing a rapid shut-down is required to prevent its being completely wrecked. In addition, with a large low-speed unit, the run-down time might be as much as an hour or more and pressure lubrication of the bearing would be essential below, say, 20% rated speed.

(9) VENTILATION OF THE ELECTRICAL MACHINE

For units of the size and speed considered here and with separate pump and turbine, i.e. unidirectional rotation, normal axial aerofoil fans with an efficiency of 50–60% would be fitted to the rotor spider.

Where running in both directions of rotation is required it is possible but impracticable to make aerofoil fans suitable for either direction of rotation. A simple alternative is to use either straight-blade (paddle) fans[11] or radial centrifugal fans with efficiencies of 10–15%. Thus for a given volume of air a straight fan may have a loss more than six times that of the axial aerofoil.

A solution which has been used on large low-speed horizontal units is to replace the rotor fans by one or more motor-driven high-speed axial-radial aerofoil fans,[25] which can be designed for an efficiency of about 65–75%.

The application of this arrangement to a large vertical unit is shown in Fig. 8. The air is drawn from the stator core through the frame by the motor-driven fan mounted between a pair of coolers. The air is then blown through the coolers to the top and bottom of the machine and guided back to the ends of the rotor. Each cooler unit thus consists of two coolers and one motor-driven fan, the units being withdrawn from the side of the machine.

In considering the relative merits of straight fans on the rotor spider and separate motor-driven fans, it has to be remembered that in large low-speed generators the fanning action of the rotor poles themselves will develop sufficient pressure to circulate a considerable volume of air. In most generators of this type additional pressure and consequently an increased volume of air is circulated through the machine by means of fans mounted on the rotor spider. The straight fans required for the 200 MW 150 r.p.m. machine would be required to circulate about 160 000 ft^3 of air per minute against a pressure drop of about $1\frac{1}{2}$ in. Assuming a fan efficiency of 10%, the power to drive the fans would amount to about 280 kW. If, however, the rotor fans were replaced by eight separate motor-driven fans to perform the same duty, assuming a fan efficiency of 65%, the total power required for the eight fans would be 50 kW.

The resulting saving of 230 kW by the use of motor-driven fans, when capitalized at £80 per kilowatt, would far more than offset the additional cost of the fans, which would be about £2 000.

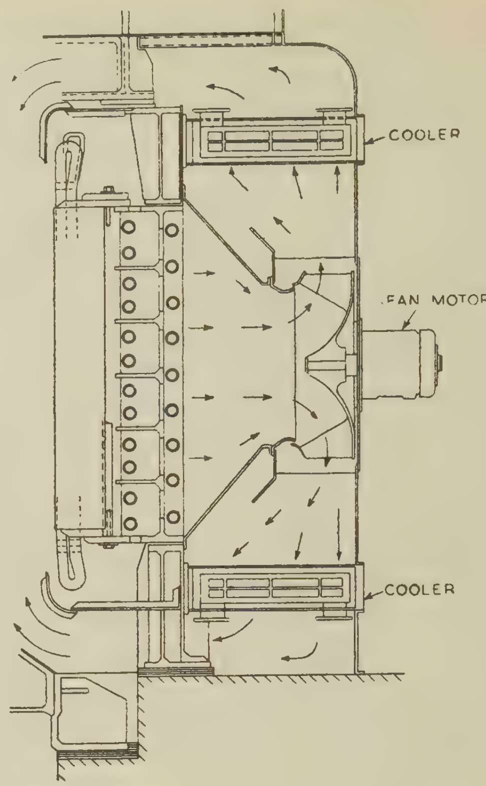

Fig. 8.—Arrangement of separately-driven ventilating fan on large hydro-electric generator.

(10) EXCITATION SYSTEM

In the majority of cases the normal arrangement of a main and pilot exciter mounted on the shaft of the main machine will be preferred on the grounds of reliability and simplicity. A separate motor-amplidyne set drawing power from the pilot exciter is included for operation in conjunction with an automatic voltage regulator of the magnetic-amplifier type. Reversal of rotation would only involve the arrangement of the brush-gear on the exciter for either direction of rotation and a change-over switch in the pilot exciter field to ensure build-up during starting. A change-over switch would also be required on the amplidyne.

If synchronous starting of the main sets were adopted, then separate motor-driven exciter sets with flywheels would be necessary, since here the fields of the main machines have to be energized at standstill. Reversal of rotation of the main sets then involves no problems in the design of the excitation system.

(11) CONCLUSIONS

The demand for large individual units can be met by ratings of 100–200 MVA and more, depending on the speed, without departing from accepted design and manufacturing techniques. The thrust bearing should be designed for pressure lubrication at starting, and it is desirable to supplement friction brakes by some form of dynamic braking.

Where reversal of rotation is required, the increased operating efficiency obtained by the use of a 2-speed synchronous machine more than offsets the higher cost of such a unit. Nevertheless the difficult problems involved in the design of such units would appear to preclude its use at present. With reversible sets starting on the pumping cycle is best carried out by direct-on-line starting on the high-voltage side of the main transformer. Reversal of rotation also makes it preferable to use separate motor-driven fans, mounted on the stator frame, for the ventilation of the main machine.

(12) ACKNOWLEDGMENTS

The author is indebted to the General Manager, A.E.I. Heavy Plant Division, Rugby, for permission to publish the paper. He also wishes to thank Mr. L. D. Anscombe and several colleagues for advice in its preparation.

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DISCUSSION ON THE ABOVE PAPER

Before the RUGBY SUB-CENTRE *at* RUGBY 11*th March, the* SUPPLY SECTION *at* LONDON 11*th November, the* NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER 24*th November, and the* MERSEY AND NORTH WALES CENTRE *at* CHESTER 14*th December*, 1959.

Mr. J. H. Aylward (*at Rugby*): Fig. 2 indicates that there is a reduction in possible output for 60 c/s machines. The reason for this is not obvious, since the curves should be based on physical limitations, but if an arbitrary limitation for length/pole-pitch has been assumed, there would be different outputs at 50 and 60 c/s.

In Fig. A I have superimposed upon the author's 50 c/s curve (Fig. 2) some curves published by Johnson and Holder.* The limits of output are, in general, determined by mechanical considerations, and the author's curves assume the less onerous condition, in that the overspeed is less. Taking this into account, the maximum outputs would be roughly in agreement for rim-type machines and high-speed disc-type machines with copper field-coils. For disc-type machines in the 400–500 r.p.m. range there is some considerable disagreement. Will the author give the basis on which his curves were drawn?

The specific case of the Bersimis generators rated at 138 MVA at 277 r.p.m. is shown in Fig. A. It is known from the test results that these could with some small modifications be up-rated to 150 MVA and still be conservatively rated both mechanically and electrically. On the basis of this it is certain, merely by increasing the core length, that at this speed a 200 MVA machine could be built. This is well above the author's curve of maximum possible outputs. By using better-quality steels but still complying with normal manufacturing limitations, even higher outputs at this speed could certainly be obtained.

It is not clear from the example in Section 5 why the starting kVA is reduced from the more normal seven times to four times its rated value for the machine alone. Fig. 3 indicates that the machine in question is, in fact, not quite a typical waterwheel generator, as the author implies, because the damper-winding and leakage reactances have been increased, as well as the damper-winding resistance. The increase in damper-winding reactance could be obtained by sinking the bars down the pole tip with some small loss of field capacity, and the increase in leakage reactance by reducing the magnetic loading. The latter results in a more expensive unit than a typical waterwheel generator of equivalent rating.

* JOHNSON, E. M., and HOLDER, C. P.: 'The Design of High-Speed Salient-Pole A.C. Generators for Water-Power Plants', *Proceedings I.E.E.*, Paper No. 1259 S, March, 1952 (99, Part II, p. 479).

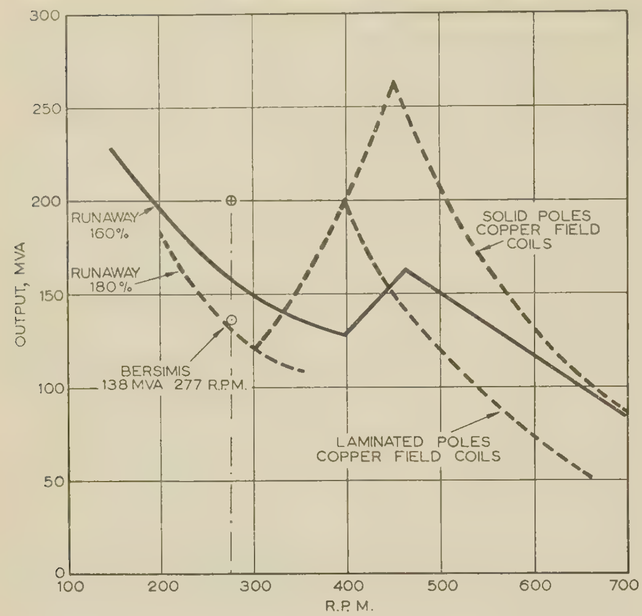

Fig. A.—Maximum output of large waterwheel alternators as a function of speed.
——— Walker's curve.
— — — Johnson and Holder's curve.

Standard practice on pad-type guide bearings is to use centre pivots, because these bearings are normally very lightly loaded; they are therefore normally suitable for both directions of rotation. For sleeve-type guide bearings the oil grooves must be suitably arranged when operation in both directions of rotation is required.

The thrust-bearing load of 400 lb/in^2 given in Section 7 is lower than that normal for waterwheel generators started without high-pressure lubrication, since present day machines are designed for 500–600 lb/in^2. There is no doubt that, for large generator/motors for pumped-storage schemes, there is some considerable advantage in using hydrostatic lubrication.

The braking duty of large generator/motors, as on peak-load waterwheel generators, is severe and the design of suitable mechanical brakes can be a very difficult problem. The phenomenon of 'hot spotting' is a characteristic of all high-duty brake systems and cannot be ascribed to deficiencies in materials or workmanship. Waterwheel generator tracks are not considered expendable, and resistance to 'heat checking' and distortion effects is important. Thus, not only must the brake shoes be considered, but the design of the track must be such that it will withstand hot-spot temperatures of 700–800° C. Observations of the colour band during braking has confirmed that hot-spot temperatures of about 800° C, and not 400° C as mentioned by the author, are actually obtained during normal braking on large high-speed generators. From the aspect of track and brake-shoe wear it is necessary to limit the duty of mechanical brakes, and for very large machines, if shutting-down speed is important, some form of dynamic braking may well be necessary. On high-inertia units the brakes should be applied in normal shutting-down at the lowest permissible speed.

Radiographic tests prove that brake pads can be obtained which contain very little, if any, metal, so that if these are used there is no danger of depositing metal dust on the machine windings.

Mr. E. H. Ball (*at Rugby*): In the early 1920's I assisted at the testing and installation of one of the earliest hydro-electric pumped-storage schemes in Great Britain. This was at a Walkerburn tweed mill, and superseded four breast waterwheels utilizing a head of about 5 ft from the Tweed and developing a total of 110 h.p. It was supplemented by steam, gas, and oil engines. This old plant was replaced by two Francis turbines, belt-coupled to a single 150 kW Peebles generator. At night the belts are moved to drive twin pumps delivering water to a reservoir 1 000 ft up a neighbouring hill; during working hours this stored water supplies a Pelton wheel driving another 150 kW Peebles generator, thus giving a total of 300 kW—sufficient to supply power and lighting for the whole mill.

Mr. P. Deriaz (*at Rugby*): At the Sir Adam Beck pumped-storage installation, comprising six 40 MW sets, the Ontario Hydro-Electric Board have chosen direct-on-line starting at full voltage. The machines are relatively close to the large generating plant, and surges on the system do not seem to present any problem. Starting-up is remarkably simple and direct-on-line starting is used for either direction of rotation for convenience and simplification of the distant control.

It is very impressive to see these large motor/generators (327 in rotor diameter) start from rest to synchronous speed in approximately 15 sec. Load can be taken immediately or the machine can be left running idle with runner blades shut. The power required to run the machine under these conditions with the runner fully submerged is just over 5% of full-load pump input.

Mr. G. Lyon (*at Rugby*): The paper is a little optimistic regarding the continued increase of thermal efficiency of coal-fired stations. The effective rate of increase of all such stations taken together will decline, since it is becoming more difficult to increase the efficiency of new stations and the rapid replacement of old sets which has been in progress will also decline as the number of over-age sets diminishes. I do not think that nuclear stations can be considered as raising the effective thermal efficiency for a number of years yet, although this assessment is on a rather different basis from that of coal-fired stations.

At the end of Section 2.2 it is not clear whether the lower efficiency quoted is due to the turbine or to the 2-speed generator/motor.

The author quotes a value of five times the field-winding resistance for the field discharge resistor. While this value is usually a satisfactory compromise between conflicting requirements, it seems to me that five has tended to become rather a 'magic number'.

The paper's reference to running machines in a station supplying some of the starting current is well phrased. With the usual h.v. busbar arrangement the proportion is likely to be about $\frac{1}{4}$–$\frac{1}{2}$ and not nearly the full starting current as is sometimes suggested.

At the end of Section 5.1 phase reversal is assumed to be done at 275 kV. There is no objection to this practice, but it may be cheaper to do the reversal at generator voltage.

Section 5.4.1 states that 4–5 kA is outside the capacity of normal circuit-breakers for 18 kV service. Circuit-breakers capable of this duty are available, although admittedly from only a few makers.

Why is it necessary to synchronize the machine while it is still running on the tap in the reduced-voltage method? Is the transfer of current surge too high if the machine is switched to full voltage before synchronizing?

Mr. D. D. Stephen (*at Rugby*): It is well known that higher outputs at higher speeds can be obtained from solid-pole machines than from the laminated-pole machines to which Fig. 2 applies. Solid-pole machines are in common use as synchronous motors and condensers, and their starting characteristics have been investigated in some detail (Reference 14). They can now be designed to take starting currents as low as squirrel-cage motors,

ly 4–5 times full load current. In addition to being more robust mechanically, these machines have a much greater thermal capacity in the pole shoes during starting, and stored-energy constants as high as 30 can be started with safety. The solid-pole design thus appears to have several advantages over the squirrel-cage one, for very large machines, since it eliminates the problems associated with the design of heavy squirrel-cage windings.

The evaluation of motor starting characteristics is not as simple as suggested in Section 5, and it is now usual to use 2-axis circuits for accurate representation. Such circuits show amounts of energy dissipated differing from the circuit in Fig. 3. On large machines the differential bar-heating effect must certainly be investigated, and one of the multi-bar-circuit 2-axis calculations should be made.

To eliminate the difficulties associated with mechanical braking and to minimize the stopping time, dynamic braking should be provided; this is merely a refinement of the braking suggested in Section 8. By inserting an external resistor of appropriate size, the braking time can be adjusted to any value down to the order of seconds. Such a resistor must dissipate the stored energy of the set, as do the mechanical brakes, but in a hydro-electric station one might expect sufficient water to be available to solve the problem of heat removal efficiently.

Mr. E. H. Harrison (*at Rugby*): The author states that the forces on the end-windings are a function of the pole pitch and that direct-on-line starting would therefore present no more of a problem than on motors having a similar pole pitch, and then refers to a 3 000 h.p. 2-pole squirrel-cage induction motor designed for direct-on-line starting. It is common practice to obtain rapid stopping and reversal of induction motors by plugging; from the data in Fig. 3 the supply current would be $\cdot 64 I_{fl}$ for direct-on-line starting and $2\cdot 75 I_{fl}$ for plugging. The simplicity and rapidity of operation using this form of electrical braking would seem to be advantageous when compared with mechanical braking. Will the author comment on the feasibility of applying plugging to the machines referred to in the paper?

Mr. C. L. C. Allan (*at London*): The paper has appeared at an appropriate time, because the increasing introduction of high-efficiency thermal plant encourages pumped-storage development.

In addition to the scheme now under construction at Ffestiniog, work is just beginning on a 400 MW pumped-storage scheme at Cruachan on Loch Awe, with four sets each of about 100 MW capacity.

Pumped-storage schemes will operate as peak-load suppliers of energy and the operational advantages of hydro-electric schemes will be equally available from them, but in addition clear economic gains will be required.

First, the cycle efficiency will be about 2/3. Economically this increases the cost of the pumping energy by $1\frac{1}{2}$. Secondly, extra fuel costs will arise from the deferment of high-merit plant and an increase in the load factor of older thermal plants. The third factor must be a saving in fixed annual charges on the pumped-storage scheme.

A reversible combined pump/turbine plant may significantly reduce capital costs and the paper deals with the problems of design and operation of such machines. A 2-stage pump/turbine will be possible with the 1 100 ft head to be used at Cruachan, but if a single-stage machine became available the savings from reduced capital cost and less space would be even more significant. Two-speed machines have not been tried in this country in large sizes and Section 2.2.1 suggests that there are real and substantial drawbacks.

When starting electrically from the system, a voltage drop of more than 3% becomes noticeable, but an occasional bump might not matter, since it might also arise from a line fault. However, pumping means a succession of starting surges, and this might be more objectionable. There is a conflict between the low starting current desired and the machine's own starting requirements.

Investigations dealing with the Cruachan 100 MW machines suggests that starting current below the full-load value will be desirable. High-pressure oil can help, but sufficient torque must be developed to accelerate the machine. Some recent tests on a 21 MW hydro-electric machine showed that, while twice full-load current did not cause breakaway, less than full-load current did if it was applied before the jacks were released.

Starting particularly affects the copper of the rotor damping winding and must not cause overheating. The effects of repeated thermal and mechanical stresses must be considered. The starting system described in Section 5.4.3 cannot start the last machine in the sequence and so auxiliary turbines might be needed on all machines. The paper correctly points out that the surge in the system from the last machine will be reduced by the contribution of the running ones, but this contribution is limited because the machines must be connected to the busbar on the high-voltage side.

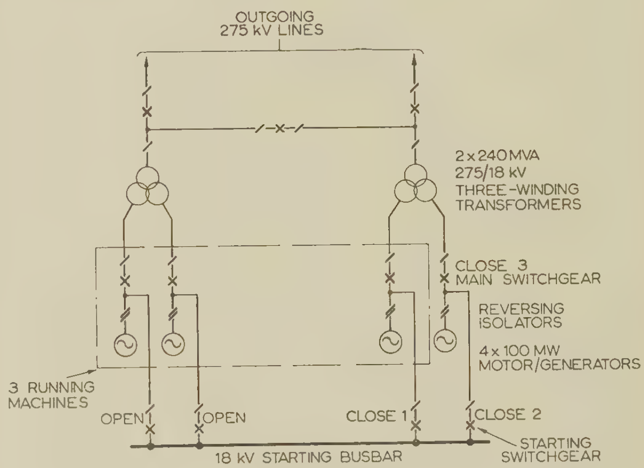

Fig. B.—Synchronous starting of four 100 MW reversible pump/turbines.

The scheme shown in Fig. B would help matters. The generator starting busbar and switchgear would allow the three left-hand machines to be run up from the fourth. The sequence would be 'close 1' and then 'close 2'. The starting surge is then shared between the two left-hand machines, the third machine from the left and the system itself. Calculations in connection with the Cruachan scheme show that the system would have to supply 65–70% of the starting surge if three machines were running and the last machine was switched in direct, but only 45–50% using the arrangement shown.

Mr. G. Lyon (*at London*): It is sometimes claimed that account need not be taken of differences in charges for energy at times of pumping and generating in assessing the merits of a pumped-storage scheme. It appears to me that such differences are important, especially in view of the relatively high capital cost of most schemes.

The paper assumes that separate pumps and turbines would be used for heads over 600 ft, but it now seems likely that reversible machines can be used for heads of at least 1 000 ft.

While increased rating of plant nearly always leads to lower cost per kilovolt-ampere for the plant itself, the lowest project cost or the lowest annual cost will not necessarily be obtained if the largest practicable size of equipment is chosen. Civil

works costs, both direct and indirect (e.g. roads and bridges), may rise disproportionately above a certain size in many sites and the effect of the outage of a particularly large unit and of the acceptance of a load of the order of 200 MW on the system requires to be taken into account. As a result, the most economical scheme may incorporate machines of ratings less than the largest that could be manufactured. In connection with the last point, what is likely to be the minimum rate of build-up of pumping load?

At the Sir Adam Beck station the pumps are immediately adjacent to generating plant of large relative capacity (total 1 600 MW compared with six 31 MW pumps). Usually the station will be located on a system in which voltage fluctuations will be noticeable, so that the permissible current for direct-on-line starting will be more limited. Published figures suggest that, on busbars supplying other consumers, voltage drops of 3% at 5 min intervals and 6% occasionally would be tolerable. These limits may require a starting current of no more than the full load value, so that jack-starting and pump de-watering may well be required. I should value the author's views on methods of admitting water to the pump when running at synchronous speed. The reactors required to limit the current may be several times the value suggested in the paper.

At the present time it seems to me that only two of the suggested methods of starting are likely to be acceptable, namely back-to-back and direct-on-line with suitable current limitation. The ease with which the latter method can be applied depends a good deal on the location of the station in the supplying system and the operating head and size of set employed.

Mr. J. Douglas (*at London*): One problem that arises is how the pump works relative to the turbine and whether it is possible to have the two conditions more or less under the maximum curve. It may be possible to have them fairly close together in their horse-power requirements. On existing sets the numbers of poles are multiples of four, and a change from, say 14 poles to 12 would give a very noisy machine.

With very large heads the runaway speed is much closer to the running speed, and it may be possible to have a much more efficient damping winding on the pole faces than with a lower speed ratio. The Hiwassee overspeed figure was about 69% and single-unit machines with very high heads give about 40%. Will the author comment on this point?

On the question of starting, a 21 MW 600 r.p.m. set on the test-bed at St. Fillans, after being jacked up and lowered, ran up smoothly with the field open at a low voltage but would not start direct-on-line, despite the application of almost full apparent power at twice full-load current. This is quite an ordinary machine with damping windings, designed for stability rather than starting. We were starting it from another machine. One difficulty is the power lost in the transformers. We had about 24 MVA on it and the other machine was about 38 MVA and fully loaded, so that the loss in the two transformers was quite large.

Perhaps one of the best ways of starting is to use a time-lag, starting up three machines in sequence, applying separate fields, running up and then synchronizing them: but if it is necessary to feed through a transformer there will be a good deal of difficulty, because of the transformer reactance. With some of the conditions we have considered it should be possible to use a run of busbars, as Mr. Allan suggests in Fig. B, since pumping takes place for a much longer time than that for which the power is required. At the same time, above Loch Awe there is always a certain amount of water which will be provided by nature, because there is a high mountain alongside it.

Mr. V. G. Newman (*at London*): Fig. 2 shows the relationship between the maximum output of large waterwheel alternators and rotational speed. Both these factors have an important bearing on the capital cost of the plant. Broadly speaking, savings in capital cost can be effected either by increasing, within limits, the size of the unit or by increasing the rotational speed. The majority of existing pumped-storage installations include surface power stations and the rotational speed of the plant is limited by purely hydraulic considerations. It is necessary to submerge the turbines and pumps sufficiently to prevent the onset of cavitation, and there is an economic limit to this, set by the cost of excavation.

It seems likely that in future a number of pumped-storage stations will be constructed underground, partly for technical and partly for amenity reasons. There would then appear to be a possibility of achieving, at a reasonable increase in civil engineering costs, the necessary submergence to make possible a considerable increase in rotational speed. For example, in the case of a machine of 200 MVA rating at 600 ft head, instead of what might be considered a normal speed of perhaps 167 r.p.m., a speed of 333 or 375 r.p.m. might be a practical proposition.

It would appear from the curve in Fig. 2, however, that difficulty will be experienced in constructing the generator/motor to operate at such a high speed for an output of 200 MVA. Presumably the rotor diameter could be reduced as the speed was increased, but I appreciate that in doing so the flywheel effect would be reduced. Is this the limitation?

Flywheel effect is in the first place a requirement imposed by hydraulic considerations and a limitation may also be imposed by system stability requirements. Can the author indicate to what extent these factors may limit the attainment of high speeds in generators of large output?

Mr. E. N. Foster (*at Manchester*): Pumped-storage schemes can be considered as three distinct types.

The first type is installations where the motor-driven pump raises the water into a reservoir and a separate turbine generator is used for power generation. Installations of this type have been in operation since the turn of the century, present no new problems and are probably the most widely used.

The second type uses a single electrical unit combined with a pump and a turbine. Generally, the pump is disconnected during generation and the problem of a suitable coupling has given rise to many solutions. Under normal operation the set runs in one direction, whether generating or pumping. However, power failure during pumping can lead to overspeeding in the reverse direction, owing to the pump acting as a turbine. Relief valves, a slip coupling as installed at Etzel and a means of driving the set by the turbine on power failure are methods employed to prevent this. The runaway speed under reverse rotation is not likely to exceed that under the action of the turbine. The design of the thrust bearing may call for special attention owing to reversal of rotation. Normally-designed spring-mounted thrust bearings have offset pivots and the method of estimation of losses is well established and verified by practical results. Has the author any comparative figures of losses for an offset spring-mounted bearing running in the two directions and can such a bearing be run in the reverse direction for the infrequent abnormal condition? Self-lubricated guide bearings would be generally suitable, the pivot-pad ones having a central pivot and the plain journal ones having left- and right-hand scrolls in the bore; experience has shown that straight grooves are adequate for journal bearings of vertical-shaft machines.

The third type of set uses a single electrical machine coupled to a single hydraulic machine. Gate leakage as a reason for use of high-pressure lubrication would appear to be equally valid for conventional machines as for any other. Some machines installed in Canada have gate leakage sufficient to maintain the sets at approximately half-speed whilst running.

The ventilation of a reversible machine should force designers to consider more seriously the true action of the rotor as a fan in conjunction with any additional shaft-mounted or separately-driven fans.

The cost comparison for 2-speed machines seems to be in doubt. Quoted values from American sources are 1·85 and 1·45 for the complete set, 1·23 for the motor and 1·77 for the turbine.

Regarding braking, whilst agreeing that some hydro-electric stations are used for base load, it is also true that in large inter-connected systems hydro-electric sets are used for peak loads and, consequently, would be shut down at least daily. The main difference is that whereas the shut-down time may be very important in a pumped-storage plant and be required to be a minimum, in a normal station the only real purpose of applying brakes is to prevent the machine rotating for a long time at a speed too low to maintain the oil film.

It is worth noting that recently a vertical water-wheel 111 MVA 167 r.p.m. generator with $H = 5 \cdot 0$ was tested at the maker's works and the brakes applied at full speed. The same brake blocks were used for the remainder of the tests, involving over 50 shut-downs.

Mr. C. Ayers (*at Manchester*): In Section 2.2.1 the capitalized value of a kilowatt is given as £80. For the installations considered, in which low-value off-peak energy is converted to high-value on-peak energy and, in particular, storage of peak power is the aim, I would expect the value to be higher. Will the author amplify his reasoning behind the choice of £80?

It appears that starting a combined pump/turbine unit is the main problem. From the method of calculation in Section 5, $0 \cdot 735 \times 10^6$ kW-sec appears to be the kinetic energy stored in the rotor and not the energy dissipated as heat. Will the author comment?

Concerning direct-on-line starting I would query the assumption of constant high voltage, which implies an infinite busbar. Even a busbar rated at 5 000 MVA has a reactance of 4% on a 200 MVA basis—a significant proportion of the total reactance in Fig. 6. Further, I wish I could have the authors' confidence that no damage will occur during starting. Surely this method is equivalent to a 100% short-circuit, the application of which, even on test, is questioned by some manufacturers.

In Table 1, additional stator temperature rises during dynamic braking are given, although only full-load current is flowing. Are these rises due to the reduction in cooling as the machine slows down?

Mr. C. J. Dickinson (*at Manchester*): In Section 2.2.1 the author attempts to justify economically the 2-speed machine and refers to its lower efficiency. The lower efficiency will be chiefly caused by increased friction and windage losses, and for the speed change considered (44 to 36 poles) the increase in windage loss may be about 80%. For a 200 MW machine this increase could well be of the order of 1 MW. Would this, with the additional bearing and harmonic losses, seriously affect the economics of the 2-speed proposition?

In Section 5.1 the author states that the voltage for which the machine is wound would influence the blocking of the end-windings. I assume that by this he means the length of coil overhang and not the voltage.

Section 5 seems to be based on the premise that all the machines in a pumped-storage station will be dual-purpose and will all be required for pumping duty at the same time. For the majority of schemes, which have natural inlet flow, would it not be more economic to provide non-pumping sets equivalent to the natural flow? The synchronous-starting arrangement would then be of prime importance.

In Section 9 the 50–60% efficiency quoted for fans mounted directly on the rotor seems high; for aerofoil fans it may be as low as 30%. I would also expect that in conjunction with the rotor poles, the efficiency of straight-bladed propeller-type fans (as opposed to the centrifugal type which are notoriously inefficient) would be of the order of 20%. For many years it has been a prerequisite of good design that the ventilation system should be based on fans integral with the rotor, for the sake of reliability. Is this not just as important for pumped-storage installations?

Mr. G. Frame (*at Manchester*): A conventional water-turbine-driven generator of the rating given by the author would have the approximate equivalent circuits shown in Fig. C.

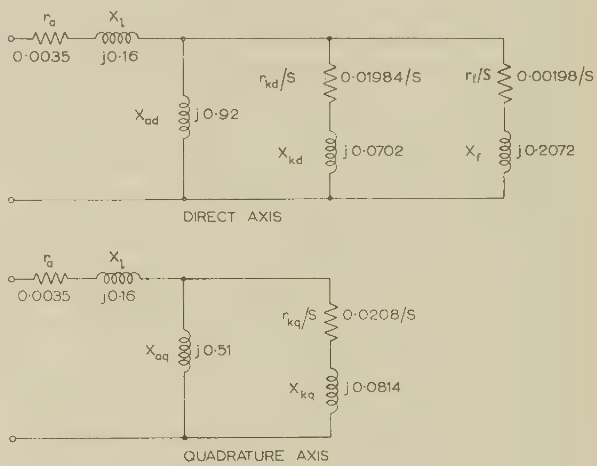

Fig. C

The starting performance of this machine would not be suitable for a motor/generator of the type considered by the author, requiring a high starting torque and a low pull-in torque. To make it suitable the values of the damper-circuit components would have to be increased to $r_{kd} = r_{kq} = 0 \cdot 246$, $X_{kd} = 0 \cdot 145$ and $X_{kq} = 0 \cdot 156$. If the damper weight is also increased to restrict the average adiabatic temperature rise to 300° C, the comparison in Table A can be made.

Table A

	Conventional generator	Pumped-storage machine
Pole tip width	18 in	18 in
Damper bar details ..	Eight ½ in-diameter copper bars per pole	Eight ¾ in × 2 in alloy bars per pole
Conductivity of bars ..	100%	1%
Total weight of bars and rings	3 000 lb	19 000 lb
Direct-on-line starting kilovolt-amperes, p.u.	4·52	3·22
Direct-on-line starting torque, p.u.	0·27	0·85
Starting time	12·1 sec	11·75 sec

From an examination of the relative values of rotor circuit components it can be seen that, whilst the negative-sequence damping is increased, the positive-sequence damping is considerably reduced. What is the author's opinion on the effect of this change on the generating performance of the machine?

Due mainly to consideration of the two axes, but also to the relative values of damper- and field-circuit impedances, the

energy absorbed by the field circuit of the pumped-storage machine is less than 1% of the total energy absorbed and no economy could be made in the damper-winding weight.

Although the average adiabatic bar temperature rise of the pumped-storage machine is 300° C, heat would be absorbed by the pole iron, resulting in an actual average temperature rise of 240° C. The closeness of these two temperatures is due to the short run-up time and the poor heat-dissipating properties of the bars. Bars would be unequally loaded, individual ones attaining temperatures varying from 170 to 290° C. The main difficulties in designing a suitable damper winding would be in accommodating the differential expansion of the bars and the thermal expansion of the large diameter end-rings.

Mr. W. H. Laurence (*Manchester: communicated*): Can the author explain why, in Fig. 2, for a given rotational speed the limiting output at 60 c/s is as much as 20% below that at 50 c/s? This implies that for a given diameter of rotor (the parameter limited by speed) the reduction in rotor space factor due to the large number of poles plus the increased core loss due to the higher frequency results in a 20% drop in output.

In Section 5 the author gives an inertia constant of 3·5. At 0·95 power factor this corresponds to an acceleration time of 7·38 sec with full-load torque applied throughout. In Section 5.3 he refers to a starting torque of 0·14 p.u. Induction motor designers are painfully aware that starting torque is not always the same as mean accelerating torque. In this case, with maximum torque arranged to occur at standstill, and allowing for the contribution of the field, a mean accelerating torque of not more than 0·1 p.u. may be expected, giving a starting time of 73·8 sec, an increase of 50% over the figure in the paper, with consequent increase in stator heating.

The damper bars are subject to forces during the starting period. The most important factor is the duration of the alternating currents, dependent in turn on the accelerating time. Induction motor experience is that trouble occurs from this cause only when the bars are not tight in the slots. If adequate measures are taken to ensure tightness there need be no doubts about squirrel-cage type windings failing for this cause. There is an additional problem with bars in salient poles, because of the differential heating, though this is not insoluble.

Mr. J. C. Beverley (*at Chester*): In some of the earlier pumped-storage schemes operating in conjunction with hydro-electric projects, the first place of decimals in the efficiency of the plant was not necessarily important, but now that the power being used for pumped-storage has been generated in stations where the second place of decimals is important, close attention must be paid to the efficiency of the installations.

In pumped-storage schemes all losses occur twice, and the paper might have placed greater emphasis on methods to improve the generator/motor efficiencies. Ventilation losses are important and are dealt with, but can the author state what other steps can be taken to reduce losses in these machines?

Reference is made in Section 2.2.1 to the gain which can be achieved in the hydraulic efficiency by using a 2-speed machine. The details of the corresponding 2-speed electrical machine would suggest that its efficiency will be somewhat less than a single-speed machine, thus absorbing some of the gain. In any case the value given for the hydraulic efficiency gain appears high in the light of developments which have taken place in variable-blade reversible pump/turbines.

Mr. E. P. Hill (*Chester: communicated*): The types of machine suitable for pumped-storage schemes are inherently of high inertia to absorb energy in case of overspeed, and their construction to withstand 60% overspeed is expensive. Furthermore, they must start up and shut down more frequently than ordinary hydro-electric plant, and must also reverse their direction of running.

It is doubtful whether any manufacturer would design and manufacture a 200 MVA change-pole synchronous machine, even if it were economically justified. Magnetic out-of-balance between poles would produce stray currents, and bearing troubles might be accentuated, as well as vibration.

The simple method of increasing the reactance during starting (Section 5.3) could be modified by making the reactor variable by saturating with direct current.

For starting purposes the torque characteristics of a d.c. motor are ideal, and the possibility of using a compensated oversize exciter to augment starting when fed from a short-rated Ward Leonard motor-generator still has attractions: its input from the a.c. side would be reasonable, since the voltage on the d.c. side is low during starting, and it would be easier to provide than a large amount of d.c. power.

With regard to starting taps and the provision of oil films before starting, unless one has worked with these very heavy rotors the effect of the film on starting conditions is surprising in the extreme. The coefficient of friction falls from 0·25 when dry to 0·125 when slightly lubricated and from 0·05 when forced lubricated to 0·004 when running. For a 100 MW machine, if the film is established before starting the breakaway torque is approximately 1% of full load i.e. 1 MW; for short-rated machines this could be provided by a 400 kW d.c. machine on overload.

The need to provide d.c. plant for dynamic braking and to turn the rotor for inspection may in certain cases cause this question to be further examined.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Dr. J. H. Walker (*in reply*):

Mr. Aylward.—The basis of the curves in Fig. 2 is given in the paper and with appropriate modifications there is no appreciable difference between the values given by Fig. A and Fig. 2.

With reference to the reduction in kVA input, an increased leakage reactance can be obtained without reducing the magnetic loading by reducing the number of slots per pole and using deep narrow stator slots.

Mr. Ball.—The installation of a pumped-storage unit in Scotland forty years ago emphasizes the pre-war tendency in this country to pioneer a new development and then to leave its large-scale exploitation to Continental manufacturers and operators. The reversal of this attitude since the war is evidenced by the building of the Ffestiniog installation rated at 300 MW and that at Cruachan rated at 400 MW—both considerably larger than any other installation in the world.

Mr. Deriaz.—These comments are valuable in showing that, where the system is stiff enough, direct-on-line starting of pumped-storage units is by far the simplest and most satisfactory method.

Mr. Lyon.—Synchronizing is carried out on the tap in the reduced-voltage method to restrict current surges to a minimum.

Mr. Stephen.—Solid-pole machines offer advantages when induction-motor starting is required; in normal industrial motors, poles are bolted on to the rotor body and there is thus ample contact area available for the flow of quadrature currents during starting. However, with large hydro-electric generators subject to overspeed, the bolted construction is usually inade-

quate and it is necessary to use dovetails to attach the poles to the rotor body. With this arrangement the contact area between pole and rotor body may be relatively small and indeterminate, and thus lead to sparking and burning at the dovetails during run-up.

Mr. Harrison.—Plugging increases the loss to be dissipated in the squirrel-cage winding by a factor of about four, and it would lead to an increase in the size and therefore in the cost of the machine to permit a satisfactory squirrel-cage winding to be fitted in the pole faces.

Mr. Allan.—The arrangement shown in Fig. B provides an ingenious solution to the problem of reducing the starting current without unduly complicating the switching. This system has the further advantage that, if conditions permit pumping over a relatively long period during the night or at week-ends, there would be no need for the line-start of the fourth machine.

Mr. Douglas.—I assume that the speaker refers to 2-speed machines. In a 24-pole machine it is possible to obtain 20- or 28-pole speeds by short-circuiting four poles on the rotor; in a 12-pole machine it is possible to obtain 10- or 14-pole speeds by short-circuiting two poles on the rotor. Recent experimental work carried out by my firm shows that this short-circuiting of poles does not necessarily lead to excessive noise or vibration.

The lower overspeeds possible with a single hydraulic unit would permit either a higher output at a given speed or a cheaper machine for a given speed and output.

Mr. Newman.—An output of 200 MVA at 333 r.p.m. is certainly, and at 375 r.p.m. probably, practicable with special construction of the rotor (see Fig. A). This construction is necessary to maintain a large diameter in order to avoid an excessive length of core. Under these conditions the reduction in the flywheel effect may be small.

In general, solid-disc rotors have a natural value of flywheel effect which usually can only be increased by increasing the size of the machine; in chain-rim rotors the flywheel effect can be varied between wide limits by adjusting the radial depth of the rim.

Mr. Foster.—Experimental data concerning losses in spring-mounted bearings capable of running in either direction of rotation are sparse. The figures given in the paper refer to the pivoted-pad type of bearing. Since there is no real hydrodynamic difference between the pivoted-pad and spring-mounted bearing, data valid for the former are equally valid for the latter.

Mr. Ayers.—The capitalized value of losses given in the paper was taken from Reference 3, which gives £87/kW for a pumped-storage installation with a 200 ft head and £47/kW for a 1 000 ft head.

For all practical purposes the energy dissipated by the squirrel-cage winding during starting may be assumed to be equal to the kinetic energy stored in the rotor.

That the stator winding will sustain no damage during starting is confirmed, not only by the experience of my firm over a number of years, but also by that at Adam Beck.

Table 1 assumes that at the instant of initiation of dynamic braking the stator windings are at rated temperature and there is no dissipation of heat from them during the stopping period. The temperature rises given in the Table thus represent the additional heating due to dynamic braking.

Mr. Dickinson.—The increase in windage loss of 1000 kW for a 20% increase in speed appear to be excessive, and my own calculations give a figure less than a third of that quoted. This figure is obviously affected by the ratio of core length to pole pitch and also by the design of the fans, and can be reduced by using the separate constant-speed fans described in the paper. Fan efficiencies quoted in the paper are actual test figures. Reliability of the ventilating system could be assured by using several fan units and rating them so that with one fan cut out the remaining fans would permit rated load to be carried.

Mr. Frame.—The effect of changes in the positive- and negative-phase-sequence damping on the generating performance of the machine would have to be investigated, in conjunction with the characteristics of the system, on a network analyser.

In Table A the total weight of bars and rings of a conventional generator is given as 3000 lb. I consider this to be low and on a machine of this size would prefer a weight of bars and rings of more than double this amount.

Mr. Laurence.—In Fig. 2 the ratio of core length to pole pitch is 4, so that at a given diameter, a 60 c/s machine has a 20% smaller pole pitch than one for 50 c/s, and thus a 20% smaller length of core, giving a 20% reduction in output for the 60 c/s machine.

The 50% increase in starting time suggested here is really not realistic since the squirrel-cage winding would not be designed to give maximum torque at standstill.

Mr. Beverley.—Since a reduction in losses implies, in general, an increase in the machine cost, to design for the best values the capitalized value of these losses is required. If the capitalized value is about £80/kW, it is probably worth using high-grade transformer sheet for the laminations and non-magnetic material for the duct spacers and pressure fingers. A further improvement is obtained by reducing the current density in the windings to a figure below that imposed by temperature guarantees.

Mr. Hill.—In general I share Mr. Hill's doubts concerning the economic justification for the use of 2-speed pumped-storage machines. Nevertheless, recent theoretical and practical investigations carried out by my firm show that the design and manufacturing problems in such units are far from insoluble.

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RESEARCH ON THE PERFORMANCE OF HIGH-VOLTAGE INSULATORS IN POLLUTED ATMOSPHERES

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SUMMARY

The paper describes the work which has been carried out at the Croydon Insulator Testing Station during the last 15 years on the performance of insulators in humid and polluted atmospheres. Various types of line and substation insulators have been investigated, and the results obtained with insulators for working voltages of up to 380kV are presented. Methods of surface treatment to improve insulator performance are also discussed. Work on experimental insulators made from plastics is described. An account is given of recent work on insulators for high-voltage d.c. operation. The use of artificial salt-pollution tests to simulate service conditions is also discussed.

(1) INTRODUCTION

With the advent of the Grid system in 1928, and the operation of 132kV lines for the first time in this country, difficulties were experienced due to insulator flashover in industrial districts, in spite of the fact that the lines were very adequately insulated in accordance with the standards prevailing at that time. These difficulties were first encountered in the Glasgow area, and in 1930 the Central Electricity Board asked the National Physical Laboratory to investigate the problem on a site at Dalmarnock power station in the area where insulator flashovers in service were being experienced. Measurements were made of the power factor and impedance of various types of insulator operating in foggy and polluted atmospheres, and useful data were obtained on the electrical characteristics of insulators under these conditions.[1]

Subsequently, however, when the Grid was commissioned in other areas, similar difficulties were experienced in industrial districts in England, and on one occasion, for example, 19 flashovers occurred in a single night (19th–20th December, 1933) on 132kV lines in South-East England. Accordingly, in 1934 the Central Electricity Board set up a permanent testing station at Croydon to carry out research on the performance of high-voltage insulators in polluted atmospheres and on related problems. As a result of the work at this station, the mechanism of surface flashover was elucidated, and a testing technique was developed for assessing the performance of insulators operating in polluted atmospheres.[2, 3] It was then possible, with the co-operation of the insulator manufacturers, to select, or when necessary to design, insulators with improved characteristics to give a better performance in service. Criteria of performance have been embodied in specifications, and the original level of insulation increased so that a much improved service performance has been obtained.

Even so, failures due to industrial pollution still occur in appreciable numbers; for example, in the period 1951–55 there was 0·25 fault per 100 route-miles of 132kV line per year. Flashover due to the deposition of salt on insulators sometimes causes widespread trouble, especially in western coastal districts, and is essentially a phenomenon similar to flashover due to industrial pollution, although there are some important differences. The average number of flashovers due to salt storms during 1951–55 was 0·35 per 100 route-miles of 132kV line per year. Thus, industrial pollution and salt storms together account for 0·6 fault per 100 route-miles per year, and constitute a source of trouble second only to lightning (average fault rate of 1·1 faults per 100 route-miles of 132kV line per year). Industrial pollution may decrease in future, but trouble due to salt storms is likely to increase as more power stations are built on coastal sites. Moreover, difficulties due to surface flashover tend to become more severe as the voltage is raised, even if the insulation is increased in proportion. Failures due to lightning on the other hand generally decrease as the insulation level is increased. It therefore appears that surface flashover of high-voltage insulation, particularly in coastal areas, is likely to present a problem for many years.

Accordingly, since the last account of the work at Croydon was published in 1942, research has continued, particularly on insulation for 275 and 380kV systems. Recently research has been started on the performance of high-voltage d.c. insulation in polluted atmospheres—a subject on which little information is available. New insulating materials and new designs of insulator, and various kinds of surface treatment have also been studied. It is the object of the paper to present the main results obtained during the last 15 years.

(2) EXPERIMENTAL METHODS

The main method consists in energizing the insulator at its maximum working voltage in the polluted atmosphere at the Croydon Insulator Testing Station and recording the leakage current and any flashovers which may occur. A test duration of several months is normally required in order to build up a surface deposit as in service, and to cover a range of weather conditions. The test gives a direct measure of performance, and its value is enhanced when a comparison with an insulator of known pollution record can be made.

The method was fully described[3] in 1942 and has not been greatly altered since then. The leakage current of the energized insulator is measured using the circuit shown in Fig. 1. The 50c/s operating currents for the flag indicator and surge counter are 150 and 25mA, respectively. In addition, the leakage current of some insulators is continuously recorded on 1in/hour recording instruments. For the detailed study of leakage-current surges, a cathode-ray or Masson oscillograph can be put in circuit. Moreover, voltage-distribution measurements on the insulators are taken from time to time.

The object of the tests is to determine the susceptibility to flashover of each design in a wide variety of weather conditions which will be encountered in service. Random variations give

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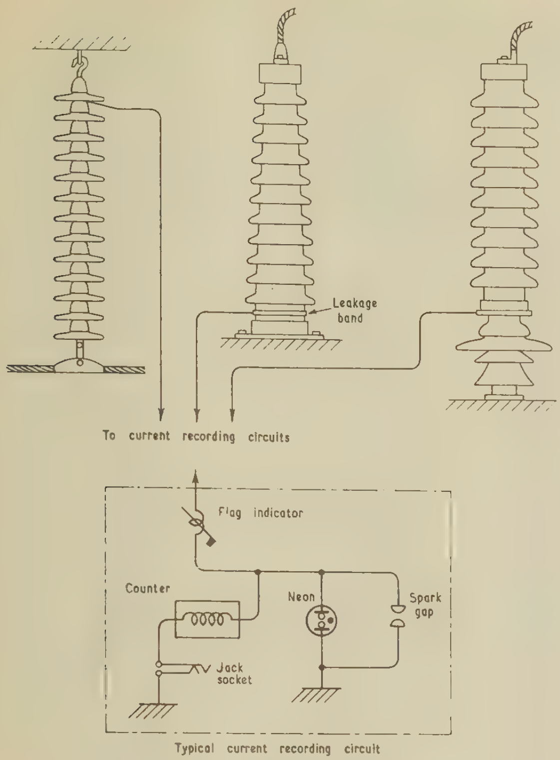

Fig. 1.—Method of recording insulator leakage current.

rise to occasional anomalies, such as the flashover of the longer of two insulators with the same shed configurations before the shorter, under apparently identical test conditions. For this reason, small differences in insulator performance are generally not significant.

The evaluation of performance by counting leakage-current surges greater than 25 mA has proved generally satisfactory in comparing plain porcelain or glass disc insulators, but it is not so satisfactory for comparing insulators of different types, nor is it entirely satisfactory for comparing greased, oil-filled or resistance-glazed insulators. In all cases, flashovers must be the final criterion of performance, but surges exceeding 25 and 150 mA are useful indications of the state of the insulator.

The test voltages in use are 85 kV (50 c/s a.c.), 175 or 231 kV (50 c/s a.c.) and 115 kV d.c.

The three alternating voltages are the maximum continuous phase-to-earth working voltages for 132, 275 and 380 kV systems. The direct voltage relates similarly to the cross-Channel cable connection.

The 50 c/s voltages are provided by an 85 and a 250 kV transformer, each with a full-range regulator. The d.c. supply is obtained by half-wave rectification of the 85 kV voltage, initially using a ballast capacitor of $0\cdot019\mu F$ capacitance, which was subsequently increased to $0\cdot19\mu F$.

A measure of the severity of pollution is the rate at which solids are deposited from the atmosphere and the amount of sulphur dioxide in the air. Typical figures for the solids deposited during the six winter months at Croydon Testing Station are 78 tons/mile^2 per month in 1951–52 and 76 tons/mile^2 per month in 1952–53. These figures compare with 9·1 and 9·2 tons/mile^2 per month for these two winters at Leatherhead, which is a semi-rural area.

The average amounts of sulphur oxides in the atmosphere in the winters of 1951–52 and 1952–53 measured by the lead-peroxide method were 2·4 mg of sulphur trioxide per 100 cm^2 per day at Croydon and 0·73 mg at Leatherhead; these figures correspond approximately to average concentrations of seven and two parts of sulphur dioxide per 100 million parts of air.

In addition to the natural pollution method, an artificial pollution test is being developed to evaluate insulator performance in coastal regions subject to salt storms. A spray of salt solution is blown on to the insulator energized at a constant voltage approximately equal to the service voltage. Its performance is observed visually and by measuring and recording the leakage current in the same way as for the natural pollution method. A 15% common-salt solution is pumped into the inlet side of a 7·5 h.p. fan which breaks it up into a fine spray, fairly even in density up to a height of 6 or 7 ft and a distance of 25 ft or more from the fan and completely enveloping the insulator. The criterion which has so far been used with this method has been the time to flashover, the recording instruments being required mainly to ensure that conditions approximate to those in actual pollution. This method gives results in a few hours, but more needs to be known of natural salt pollution before it can be used safely as a direct measure of performance in service. It can, however, be used to compare insulators, and its value is not limited to salt-storm conditions since some features of coastal and industrial pollution are similar.

(3) INVESTIGATIONS OF INSULATOR CHARACTERISTICS

Investigations covered a wide range of line, bushing and post insulators, drawings of which are shown in Figs. 2, 3 and 4. The figure and item numbers of the insulators are used in the Tables and text for ease of reference.

(3.1) Effect of Insulator Shape and Dimensions

(3.1.1) Suspension Insulator Length.

Table 1 gives the results of tests on anti-fog and standard insulators of different lengths (measured from the ball at one end to the socket at the other). These results are a yardstick against which other figures for surge counts and times to flashover can be compared.

The effect of varying the number of units can be clearly seen from the results for the 6-, 8- and 10-unit anti-fog insulators of the same type (Fig. 2, No. 1). The results for 10-unit anti-fog insulators of only slightly different designs (Fig. 2, Nos. 2, 3 and 4) show quite a wide difference in performance, even when allowance is made for different leakage path lengths.

It has been suggested that on some lines which have been uprated and where consequently the space available on the towers is smaller than usual, a shorter string of heavy-duty glass insulators (8 000 lb working load) (Fig. 2, No. 5) could be used instead of the normal ten anti-fog cap-and-pin units used in suspension on the 132 kV system. The result of the test on the 6-unit glass insulator indicates that it is not suitable for 132 kV, although it is slightly superior to the corresponding porcelain insulator. But bearing in mind the difference in performance of various designs of porcelain insulators, this superiority need not be wholly ascribed to the material.

(3.1.2) Bushing and Post Insulators.

The tests on bushing and post insulators are less severe than those on the suspension and tension types since the compounds in which the substation insulators are erected are more sheltered from the neighbouring sources of pollution than the test towers. Comparison between the two locations is therefore difficult, but the performances of insulators in the compounds can be compared with one another.

Tests on insulators differing only in diameter have so far given inconsistent results. It seems likely, therefore, that insulator diameter has only a second-order effect.

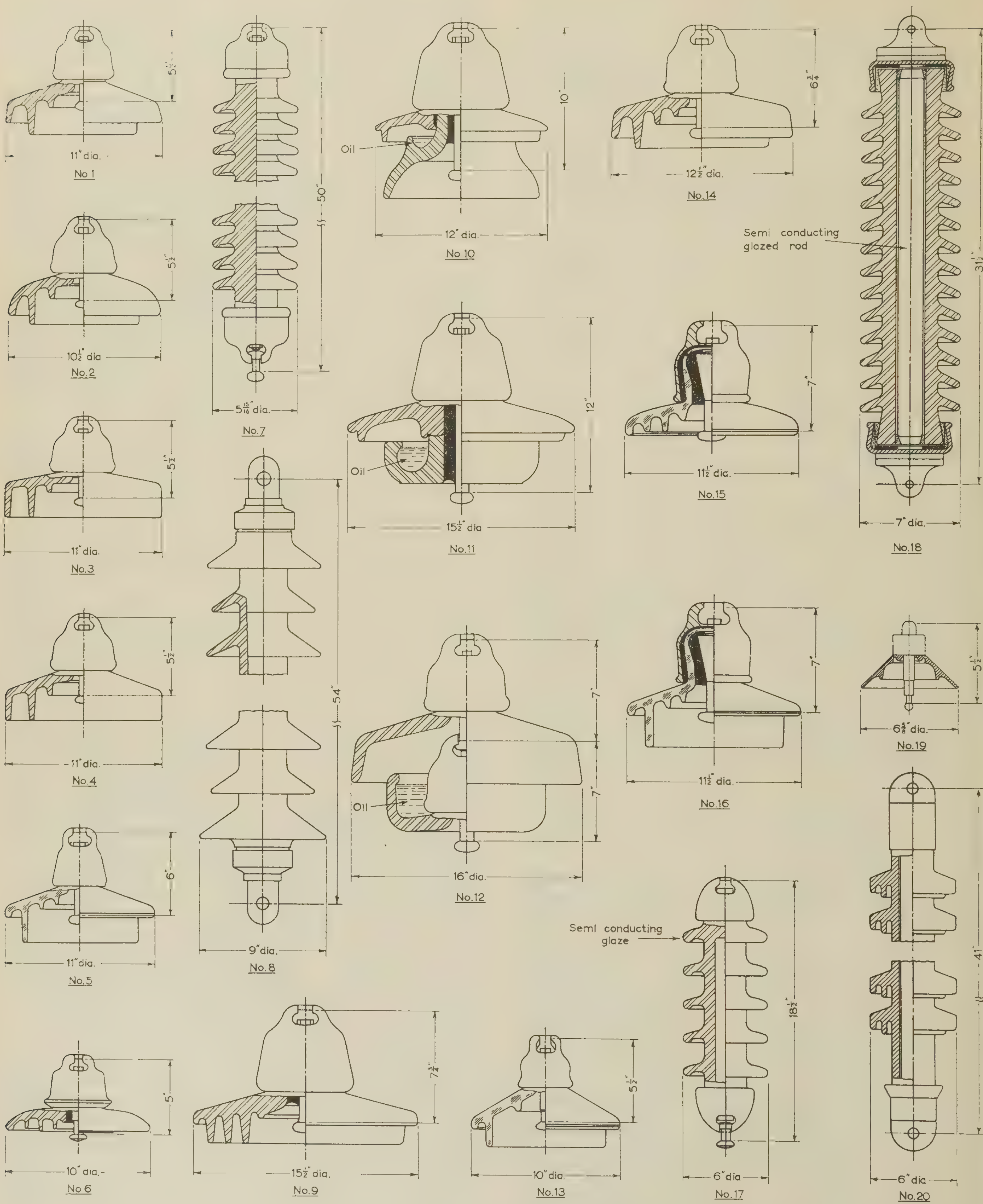

Fig. 2.—Types of suspension insulators.

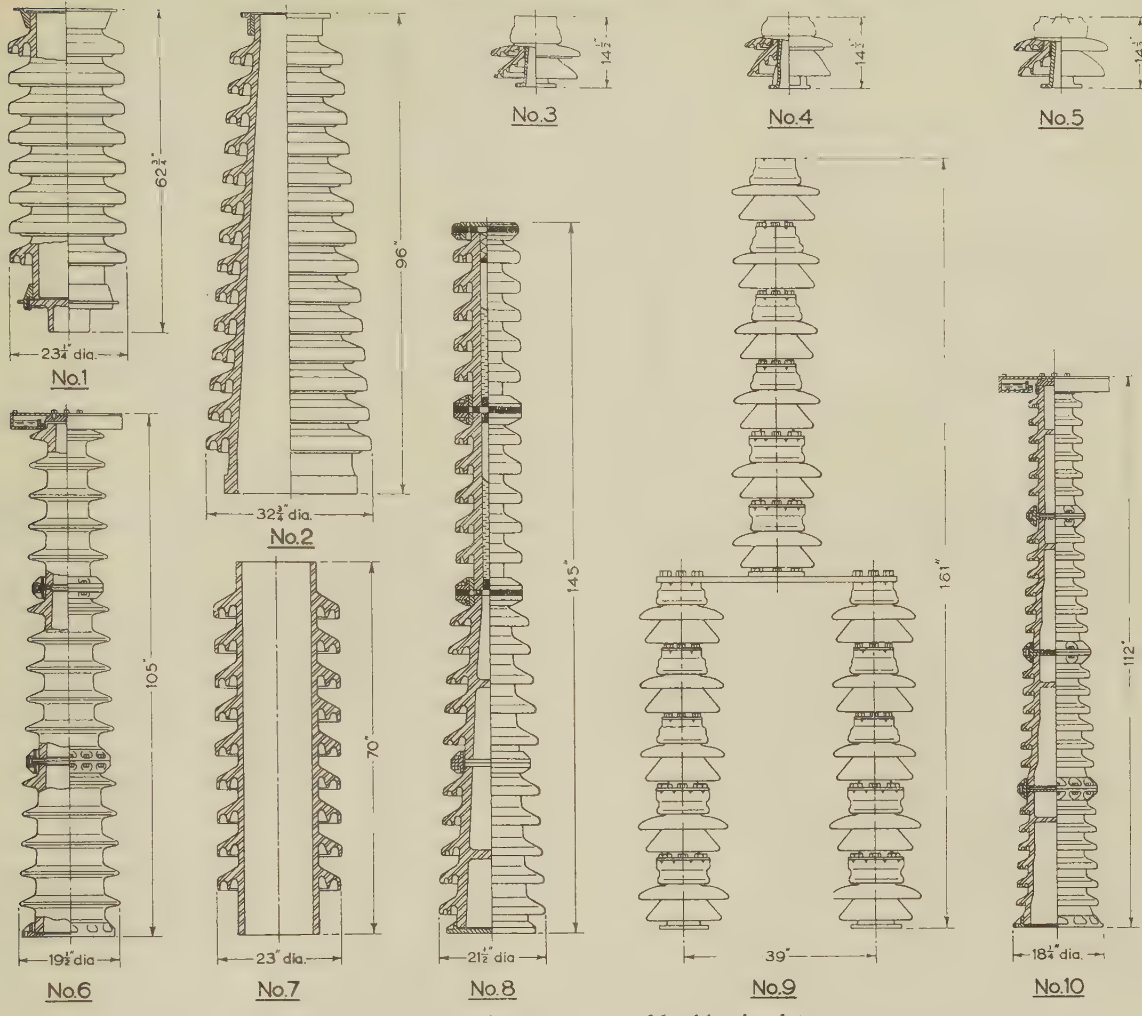

Fig. 3.—275 and 380 kV post and bushing insulators.

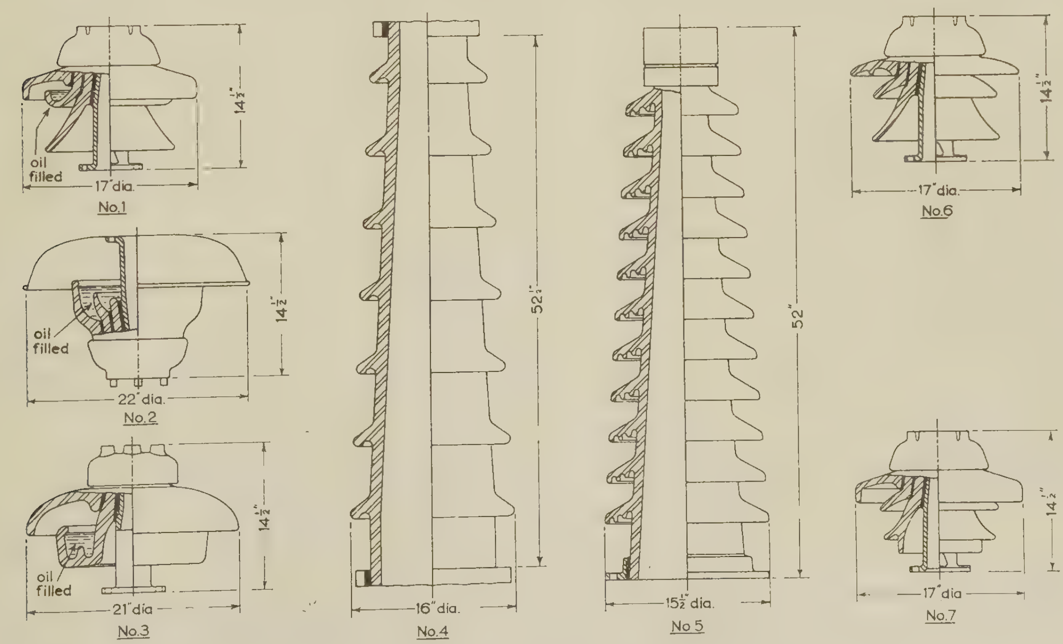

Fig. 4.—132 kV post and bushing insulators.

Table 1

PERFORMANCE OF CAP-AND-PIN INSULATORS AT 85 kV

Insulator type	Fig. 2 No.	Leakage path	Date of energizing	Months of test or to 1st flashover	No. of surges to flashover or during test	No. of flag operations before flashover
		in				
6-unit porcelain anti-fog disc ..	1	100½	16th October, 1953	37 (F.O.)	1 839	3
8-unit porcelain anti-fog disc ..	1	134	16th October, 1953	53	2 121	0
10-unit porcelain anti-fog disc ..	1	167½	16th October, 1953	53	327	0
5-unit glass heavy-duty anti-fog disc	5	84	9th October, 1953	26 (F.O.)	1 335	0
6-unit glass heavy-duty anti-fog disc	5	100½	9th October, 1953	54	1 943	1
7-unit porcelain standard disc ..	6	86	9th October, 1953	27 (F.O.)	4 660	0
10-unit porcelain anti-fog disc ..	2	160	11th June, 1953	58	2 314	0
10-unit porcelain anti-fog disc ..	3	175	10th August, 1954	44	4 022	0
10-unit porcelain anti-fog disc ..	4	170	10th August, 1954	44	1 344	0

F.O.: Flashover.

Splitting up an insulator surface, by using regularly spaced metal bands of small inter-band capacity to limit the lengths of individual discharges, has also been found to have little effect on the performance of an insulator.

(3.1.3) **Comparison of Rod (Langstab) and Disc Insulators.**

In Germany, rod insulators have proved popular, and various authors have claimed that their performance is superior to that of cap-and-pin insulators.[4, 5] On the other hand, Stolte,[6] referring to the Ruhr, where atmospheric pollution is similar to that in this country, has found an anti-fog cap-and-pin to be better than an anti-fog rod type.

To obtain further information on this question, the performance of 1-, 2- and 3-unit anti-fog rod insulators (Fig. 2, No. 7), at system voltages of 132, 275 and 380 kV, was compared with that of anti-fog cap-and-pin insulators (Fig. 2, No. 1) having approximately the same overall lengths and energized at the same time. Also 1- and 2-unit rod insulators with standard shedding (Fig. 2, No. 8) were tested at 85 and 231 kV.

The results (Table 2) show that at 175 and 231 kV the performance of anti-fog cap-and-pin insulators is superior to that of rod insulators with the same overall lengths. At 85 kV, however, the results are less definite. Although the anti-fog rod insulator has recorded a large number of surges, including two exceeding 150 mA, it has not flashed over, whereas the 9-unit anti-fog disc insulator has. However, an 8-unit anti-fog disc insulator has not flashed over despite the fact that it has been on test for a longer time.

When comparison is made between rod and disc insulators of approximately the same leakage path lengths at 85 kV, the standard shedded disc insulator can be seen to have a better performance than the standard shedded rod. On the other hand, the 6-unit anti-fog disc insulator has flashed over, while the anti-fog rod insulator, although having dangerously high surges, has not done so.

(3.2) **Surface Treatments to Increase Resistivity**

(3.2.1) **Oil.**

The use of oil in porcelain insulators is not new, the first patent on an oil-bath insulator being filed as long ago as 1878. The principle involved is the provision of a water-repellent surface, which maintains a high resistance under all conditions.

(3.2.1.1) *Oil-Bath Insulators.*

In applying the principle various forms of insulators have been adopted, but in every case there are two main elements: an oil-bath and a cowl to prevent displacement of the oil during rain and loss during high winds. Transformer oil is normally used, although sometimes (Fig. 4, No. 1) a thicker oil is specified.

Owing to the tendency of oil to creep, the entire surface of

Table 2

PERFORMANCE OF ROD INSULATORS

Voltage	Insulator type	Fig. 2 No.	Overall length	Leakage path	Leakage path/ overall length	Date of energizing	Months of test or to 1st flashover	No. of surges to flashover or during test	No. of flag operations before flashover
kV			in	in					
85	1-unit anti-fog rod	7	50	109	2·2	19th October, 1954	41	24 512	2
	1-unit standard rod	8	54	85½	1·6	10th October, 1955	13 (F.O.)	9 064	2
	9-unit anti-fog disc	1	49½	151	3·0	19th October, 1954	39 (F.O.)	953	0
	8-unit anti-fog disc	1	44	134	3·0	16th October, 1953	53	2 121	0
	6-unit anti-fog disc	1	33	100½	3·0	16th October, 1953	37 (F.O.)	1 839	3
	7-unit standard disc	6	35	86	2·4	9th October, 1953	27 (F.O.)	4 660	0
175	2-unit anti-fog rod	7	100	218	2·2	19th October, 1954	11	4 017	0
	17-unit anti-fog disc	1	93½	285	3·0	19th October, 1954	11	270	0
231	3-unit anti-fog rod	7	150	327	2·2	30th September, 1955	5 (F.O.)	3 604	0
	2-unit standard rod	8	112	171	1·5	30th September, 1955	2 (F.O.)	2016	1
	26-unit anti-fog disc	1	143	435	3·0	30th September, 1955	28 (F.O.)	1 359	2

F.O.: Flashover.

Table 3

PERFORMANCE OF COATED INSULATORS

Type	Fig.	No.	Leakage path length	Test voltage	Coating	Penetration I.P. 50/56	Drop point I.P. 132/57	Test period	Surge count	Remarks
			in	kV			degC	months		
7-unit standard disc . .	2	6	86	85	None	—	—	27 (F.O.)	4 660	
7-unit standard disc . .	2	6	86	85	Petroleum jelly	100–120 (U.W.)	55	38 (F.O.)	0	
7-unit standard disc . .	2	6	86	85	Aluminium soap base	180–210 (U.W.)	85	21 (F.O.)	3	
7-unit standard disc . .	2	6	86	85	Silicone film	—	—	4 (F.O.)	110	Microscopic film of silicone
6-unit stabilized glaze disc	2	6	73½	85	Petroleum jelly	100–120 (U.W.)	55	49 (F.O.)	4	1 flag indicator operation
6-unit stabilized glaze disc	2	6	73½	85	None	—	—	37 (F.O.)	88	
1-unit standard rod . .	2	8	85½	85	White petroleum jelly	167	44	15	0	
1-unit standard rod . .	2	8	85½	85	None	—	—	13 (F.O.)	9 064	2 flag indicator operations
5-unit glass anti-fog disc . .	2	13	72½	85	White petroleum jelly	167	44	23 (F.O.)	0	1 unit shattered on flashover
6-unit glass anti-fog disc . .	2	13	87	85	None	—	—	23 (F.O.)	1 461	2 flag indicator operations
6-unit anti-fog disc . .	2	1	100½	85	Lithium soap base	265–295 (W)	190	13 (F.O.)	1	Grease put on dirty porcelain
6-unit anti-fog disc . .	2	1	100½	85	Lithium soap base	265–295 (W)	190	16	1	Grease put on clean porcelain
7-unit standard disc . .	2	6	86	85	Silicone compound	190–230 (U.W.) Max. 300 (W)	—	11 (F.O.)	666	0·002–0·004 in thick silicone
7-unit standard disc . .	2	6	86	85	Chlorinated polyphenol	—	—	4	0	
7-unit standard disc . .	2	6	86	85	Petroleum jelly	100–120 (U.W.)	55	4	1	
10-unit standard disc . .	2	6	122½	85	Petroleum jelly	100–120 (U.W.)	55	3	0	
7-unit standard disc . .	2	6	86	85	Petroleum jelly	145 (U.W.)	62	4	0	
7-unit standard disc . .	2	6	86	85	Petroleum jelly	200–220 (U.W.)	40	4	0	
20-unit anti-fog disc . .	2	1	335	175	Petroleum jelly/wool grease	120–140 (U.W.)	45	14	0	
				231				30	101	3 flag indicator operations
7-unit pedestal post . .	3	3	245	175	Petroleum jelly	100–120 (U.W.)	55	5	0	
				231				30	1	
15-unit glass anti-fog disc	2	13	217½	231	White petroleum jelly	167	44	11	0	
								14	1	

F.O.: Flashover.
W.: Worked.
U.W.: Unworked.

the insulator soon becomes oil-covered and water-repellent. The bath is, in fact, a reservoir rather than the prime insulation of the unit, and it follows that a reasonable leakage path length is still necessary. Although metal cowls have been successfully used, insulating cowls are preferable since they contribute to the leakage path length.

Air-borne dust and dirt coming into contact with the oil surface readily adhere and the insulator soon acquires an exceedingly dirty appearance, but this does not seem to affect the performance, as the oil engulfs and impregnates the contaminants and insulates one particle from another. Operational experience has shown that oil-bath posts are, however, somewhat vulnerable to coke dust in large quantities. The carbon particles not only smother the exposed surface but tend to 'line-up' in the electric field under the oil in the bath itself.

Experience generally with the 132 kV oil-bath post insulators, both at Croydon and in service at extremely polluted sites, has been quite good, but there have been some flashovers. Flashover of one insulator (Fig. 4, No. 2), a 4-unit post with metal cowls, occurred at Croydon in fog.

Very few leakage-current surges have been recorded on any of the oil-bath insulators, even when failure has occurred (see also Section 3.2.2). Therefore, if any surges are recorded, this should be taken as an indication that cleaning and oil replacement are immediately necessary. For example, the post mentioned above (Fig. 4, No. 2) recorded no surges before it flashed over in 3¾ years. The two posts with porcelain cowls (Fig. 4, Nos. 1 and 3) have recorded no surges in 3 and 3½ years, respectively.

A 14-unit oil-bath suspension insulator (Fig. 2, No. 10) tested at 275 kV was not a success; the oil was blown out of the units and several surges were recorded (Table 4). It was therefore decided by the manufacturers that it would be necessary to use a modified design for 380 kV.

The new design (Fig. 2, No. 11) was an improvement, but it also ultimately failed because the oil was blown out of the container. Another insulator (Fig. 2, No. 12) which is better designed in this respect continues to behave satisfactorily (see Table 4).

(3.2.1.2) *Oil-Leak Insulators.*

A modified application of the principle has been introduced by one manufacturer. In this, a multi-unit cylindrical post is provided with a closed oil reservoir at the top from which there is a controlled slow leak. Thus the porcelain should become oil-covered shortly after erection.

A 3-unit oil-leak post (Fig. 3, No. 6) was energized successfully for a short time at 175 kV but flashed over very soon after the test voltage was raised to 231 kV (Table 4). Another oil-leak post (Fig. 3, No. 10) is now on test at 231 kV; its performance has been better so far, no doubt because it has anti-fog shedding to interrupt the path of any water droplets flowing down the surface.

(3.2.2) **Grease.**

Greases, like oils, are water-repellent, and since some oil-bath insulators had proved successful it seemed worth while to investigate the behaviour of grease-coated insulators.

It was anticipated that the coating would have a limited life mainly determined by two conflicting factors. Dirt would adhere to the grease surface and tend to render it inoperative; on the other hand, the grease would slowly engulf the particles and tend to restore the initial surface properties. It was clear that the grease layer would have only a finite absorbing capacity and in time would cease to be effective, owing to saturation and also, possibly, as a result of oxidation or chemical attack. However, the useful life could be determined only by direct trial.

Accordingly some trials were started at Croydon in September, 1954, using thick hydrocarbon greases on some short suspension insulators energized at 85 kV. Most of the greases used had drop points of 45° C or over, so that adhesion should be adequate in warm weather. A thick coating (of at least ⅛ in) was applied by hand.

The results of these and subsequent tests are given in Table 3, and it may be seen from this and the relevant entries in Table 4 that insulators coated with certain greases gave a very good performance, bearing in mind their short lengths.

The longest life of almost 3½ years obtained on a 7-unit insulator, together with results on four other insulators, indicated that petroleum jelly was the most effective of the greases tried, and that the safe working life is about 2 years. It was established that the porcelain should be clean before grease is applied. The heavy greases initially used were not easy to remove, preparatory to regreasing, and lighter grades are employed in some of the trials in progress. Up to the present the indications are that loss through melting in hot sun is less than was feared with such grades. It will be seen that, as with oily insulators, little information on insulator condition can be obtained from the leakage-surge count, very few surges being counted before flashover in most cases.

Divisional and Area Board trials have been made, following the promising early results obtained both at Croydon and in the South Wales Division, where, independently, experiments were started in 1953. The South Wales tests had, as their original object, the easier removal from some line insulators of a particularly troublesome deposit from a calcium-carbide factory; it was soon found that not only was greasing effective for this purpose but that the need for cleaning was partly obviated as well. Thus a considerable amount of service as well as research experience exists, and where a thick enough coating has been used with regular replacement, good results have been obtained.

It has been found that glaze can be damaged by the intense heating brought about by leakage currents of high local density occurring under a thin layer of grease. An example of this is shown in Fig. 5. Such damage should not be generally of great

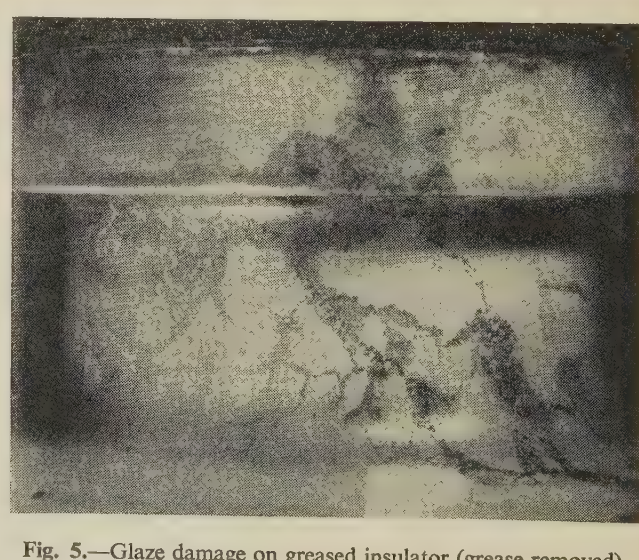

Fig. 5.—Glaze damage on greased insulator (grease removed).

consequence, but, in porcelain under high loading, the notch effect may cause the local stress to exceed the ultimate tensile stress of the porcelain so that a crack is formed.

Table 4

PERFORMANCE OF 275 AND 380 kV INSULATORS

Energizing voltage	Insulator type	Fig.	No.	Overall length	Leakage path	Date of energizing	Months of test or to first flashover	No. of surges to flashover or during test		No. of flag operations before flashover
								275 kV	380 kV	380 kV
kV				in	in					
175	2-unit capacitor voltage transformer housing	3	1	118	323	5th November, 1953	22	110	—	—
	Current transformer bushing ..	3	2	96	278	8th December, 1953	21	115	—	—
	14-unit oil-filled suspension ..	2	10	140	311	12th April, 1954	17	14	—	—
	15-unit anti-fog discs	2	9	116	342	10th August, 1954	13	442	—	—
	19-unit anti-fog discs	2	1	104½	318		13	329	—	—
	17-unit anti-fog discs	2	1	93½	285	19th October, 1954	11	270	—	—
	2-unit anti-fog rod	2	7	100	218		11	4017	—	—
175 to 16th September, 1955 231 from 30th September, 1955	8-unit pedestal post	3	3	116	280	21st January, 1953	36 (F.O.)	244	916	0
	8-unit pedestal post	3	4	116	279½	11th August, 1953	29 (F.O.)	10	446	0
	8-unit pedestal post	3	5	116	286	15th September, 1953	38	0	1779	0
	3-unit oil-drip cylindrical post ..	3	6	105	140	13th June, 1955	4 (F.O.)	1	14	0
	7-unit greased pedestal post ..	3	3	101½	245	19th April, 1955	35	0	1	0
	20-unit greased anti-fog discs ..	2	1	110	335	10th August, 1954	44	0	101	3
231	10-unit pedestal post*	3	5	145	359½	9th November, 1956	17	—	172	0
	2-unit anti-fog cylindrical post ..	3	7	140	340	19th December, 1956	15	—	475	0
	4-unit anti-fog cylindrical post ..	3	8	145	394	17th January, 1957	14	—	2710	5
	16-unit pedestal 'inverted Y' post	3	9	161	385		12 (F.O.)	—	230	3
	4-unit oil-drip anti-fog cylindrical post	3	10	112	222	29th November, 1956	16	—	0	0
	26-unit anti-fog discs	2	1	143	435	30th September, 1955	28 (F.O.)	—	1359	2
	21-unit anti-fog discs†	2	14	142	404		30	—	1790	3
	18-unit anti-fog discs	2	9	139½	414		30	—	1799	0
	19-unit high-capacity glass standard discs	2	15	133	257	3rd December, 1956	16	—	305	1
	19-unit high-capacity glass anti-fog discs	2	16	133	299		16	—	15	0
	20-unit oil-bath suspension ..	2	12	140	305	30 September, 1955	30	—	0	0
	12-unit oil-bath suspension ..	2	11	144	274½		15 (F.O.)	—	32	0
	2-unit standard rod	2	8	112	171		2 (F.O.)	—	2016	1
	3-unit anti-fog rod	2	7	150	327		5 (F.O.)	—	3604	0
	15-unit greased glass anti-fog discs	2	13	82½	217½	11th January, 1956‡	25	—	1	0

* Semiconducting glaze fringe on top two units.
† One unit removed 9th November, 1956.
‡ Removed 3rd December, 1956, regreased and replaced 3rd January, 1957, and again removed on 10th March, 1958.
F.O.: Flashover.

(3.2.3) **Other Surface Treatments.**

In addition to hydrocarbon oils and greases, two silicones and one chlorinated polyphenyl resin have been tried as surface treatments on 7-unit strings of standard disc insulators energized at 85 kV.

One of the silicone-treated strings had a greasy compound applied in a solvent to give a very thin surface layer. A thicker layer of silicone grease would, no doubt, give results comparable with those obtained with a hydrocarbon grease, but the cost of the material is over 40 times as great.[7] The other string was treated by a manufacturer, a thin film being applied. The results are given in Table 3. It will be seen that the two silicone-treated insulators gave a poor performance; the greased one presumably failed owing to dirt saturation of the layer and the other through rapid weathering of the film. The trial with the polyphenyl resin has not been in progress long enough for any firm conclusions to be drawn.

(3.3) Control of Voltage Distribution

If a fairly uniform voltage distribution could be maintained over an insulator surface under all conditions, flashover would not occur. It was demonstrated at Croydon in 1940 that a stable voltage distribution on a string of insulators can be achieved if the resistance of each unit is such as to permit a current of about 1 mA to flow through the insulator. It is not necessary for the resistance to be less than that of the layer of deposit which is in parallel with it. The resistance also prevents the surface resistance of the unit from becoming too high, and thus reducing the voltage on the remaining units.

The power loss per 132 kV insulator is 76 watts, which corresponds to 1 kW/mile of 3-phase line. This is small in comparison with other losses, and moreover the power dissipated in the insulator may be useful in keeping its surface dry.

The first experiments were made with a fixed 10-megohm resistor incorporated in each insulator unit in various ways. These insulator strings were shown to have an excellent performance under severe conditions, but there are objections to insulators of this type on the ground of complication and the long-term stability of the fixed resistances. Accordingly alternative methods were pursued.

One of the most attractive methods of obtaining the required resistance is to coat the porcelain with a semiconducting ceramic glaze having the desired surface resistivity—about 10 megohms. English manufacturers have been successful in producing a suitable ceramic semiconducting glaze,[8, 9] and insulators glazed with this material have been manufactured. Insulators of this type ('stabilized' insulators) have been tested at Croydon. It has been confirmed that the voltage distribution is effectively controlled and that the performance is very greatly improved in comparison with that of similar insulators with normal glaze. For example, Fig. 6 shows the leakage currents of a normal rod-type porcelain insulator (leakage path, 109 in) and a sealing end with a semiconducting glaze (leakage path 68 in), both operating at 132 kV. It will be noted that, when the relative humidity reached 80%, leakage-current surges occurred on the normal porcelain insulator and increased to over 100 mA as the humidity increased to over 90%. The leakage current of the insulator with semiconducting glaze remained relatively steady, however, and showed no sign of surges.

Unfortunately the life tests at Croydon showed that the glaze deteriorated in less than a year, particularly in areas adjacent to the metal fittings where contact was made between the cement and the glaze, although considerable improvement was obtained by using a band of higher-conductivity glaze at the junction between the metal fittings and the glaze.[9] The deteriorated glaze was non-conducting, and spark discharges occurred across

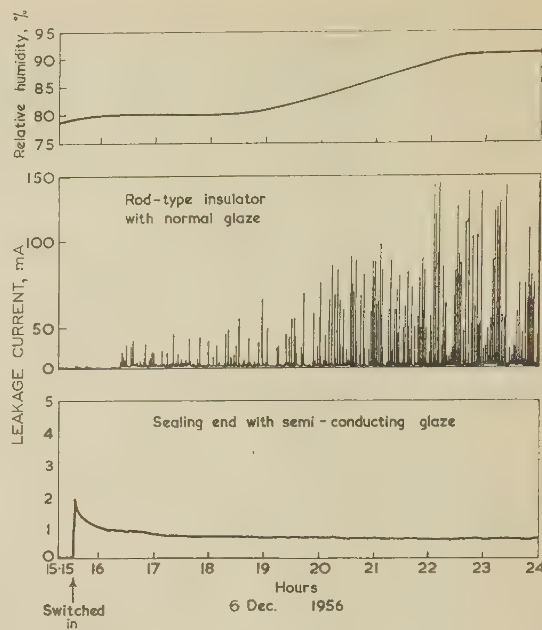

Fig. 6.—Leakage currents of normal and semiconducting glaze insulators.

the affected area, resulting in still further destruction of the glaze and loss of voltage control. An intensive investigation of the electrical properties of semiconducting glazes[10] was started with the object of elucidating the deterioration mechanism. It was shown that the deterioration of the glaze was caused by a kind of electrolytic corrosion, and a testing technique was evolved to assess the vulnerability of various types of glaze. This, in turn, has led to the development of a new barium-ferrite glaze, which it is hoped may be more resistant to service conditions.[11] The work also indicated that the deterioration would occur only in the presence of moisture to form an electrolyte, and it follows that the semiconducting glazes should have a satisfactory life in perfectly dry conditions or immersed in oil. Greasing the surface of a stabilized disc insulator has not been successful (see Table 3). Other stabilized insulators have been made with internally-glazed components of the appropriate resistance, although this only gives control of the voltage on the whole unit or section and not over all parts of the exposed surfaces. In this type of insulator with internal resistances, care must be taken to permit adequate dissipation of heat, particularly when the ambient temperature is high or in strong sunlight. Most semiconducting ceramic glazes have a high negative temperature coefficient (an increase of 30° C may halve the resistance), so that thermal instability will result if the current exceeds a limiting value, and several failures have occurred in this way. Semiconducting materials with smaller, or even with positive, temperature coefficients have been made, but have not yet been incorporated in a ceramic glaze.

These difficulties have prevented the widespread adoption of insulators with semiconducting ceramic glaze, but it should be noted that a limited amount of satisfactory service has been obtained. It is apparent from the results of the work outlined that maximum service life is likely to be obtained on insulators of cylindrical shape using as small a stabilizing current as possible consistent with adequate voltage control. Accordingly service trials on cap-and-pin line insulators were soon abandoned in favour of trials on bushings, cable sealing-ends, rod and cylindrical insulators. Some 42 cable sealing-ends (stabilizing current of about 0·5 mA) have been installed on the 132 kV system and

have given satisfactory service for more than ten years. In one instance flashover occurred, but the resistance was rather high for adequate stabilization. Parallel life tests made at Croydon have indicated only slight glaze deterioration after ten years. Stabilized insulators are also in service on 132 and 275 kV bushings and on 132kV air-blast switchgear. Rod-type insulators have been used on a 132 kV line as an experiment, but the resistance was too high for adequate voltage control and one flashover occurred. Semiconducting glaze has also been used successfully to control voltage distribution in lightning arresters.

The voltage distribution can also be controlled by increasing the capacitance of the insulator units sufficiently to provide a stabilizing current of about 1 mA. For a typical insulator unit a capacitance of about 300 pF, or ten times the normal value, would be required. Experiments were therefore made, initially in 1943, using tubular units containing high-permittivity ceramic capacitors. The voltage distribution was found to be satisfactorily stabilized, but after a short time the capacitors punctured, and it appears that improved materials will be required to withstand these conditions.

A recent development by an English manufacturer is the high-capacitance glass insulator unit, in which the capacitance is increased by a specially designed head with the glass thickness reduced, but still sufficient to withstand the impulse voltage test. Two 19-unit strings with stabilizing currents of about $1\frac{1}{4}$ mA have been tested at 231 kV (Table 4). The performance is promising in view of the short leakage path lengths.

(3.4) Plastics

In the search for improved insulation, new materials are constantly reviewed, and those showing possibilities of development as outdoor insulation have been the subject of special investigations. Many synthetic resins and plastics are used very successfully as high-voltage insulation indoors and especially under oil, but hitherto exposure of such materials has resulted in rapid deterioration, particularly under electric stress.

It has not yet been possible to produce a plastic insulator which will withstand outdoor weather conditions, but a brief account of researches that have been carried out is included here to indicate the obstacles which must be overcome before further progress can be made.

(3.4.1) Polythene.

Polythene offers some promise for use as external insulation because of its waxy nature, high electric strength and resistance to tracking. Accordingly trials have been made in which it has served as outdoor insulation in various ways. Owing to its low mechanical strength, insulators made from it must be of a composite design incorporating a reinforcing element. White polythene was used in the earliest trials, in which a skin of the material, about $\frac{1}{16}$ in thick, was flame-sprayed on to standard disc insulators and an 11-unit string was energized at 85 kV. Extensive cracking of the skin took place within one year, possibly as a result of the effect of ultra-violet light.

Later some solid-polythene disc insulators (Fig. 2, No. 19) were tested for a manufacturer for their electrical properties only. The performance of the 7-unit insulator at 85 kV was promising, having regard to the short leakage path of $57\frac{1}{2}$ in. However, failure occurred in four years after three units had punctured owing to erosion of the polythene near the pins. There were no signs of ultra-violet-light attack at the end of this time.

Two polythene/laminated-wood rod insulators have been tested, the second of which is shown in Fig. 2, No. 20. Each insulator had a resin-bonded wood-laminate core inside a black polythene tube, sealed at the ends and with the spaces between rod and polythene filled with polythene grease. Both insulators failed in only one month, the first because of its very short leakage distance of 30 in, and the second through severe tracking associated with voids of up to $\frac{1}{2}$ in diameter which were later found in the casting. Black polythene was used to give an improved resistance to ultra-violet light, but the carbon loading appears to have increased the susceptibility to tracking in this instance. It appears that the dangers of ultra-violet-light attack on solid white polythene are less than the risk of tracking through carbon loading. The results indicate that further work on polythene insulators would be worth while.

(3.4.2) Resin-Bonded Glass Fibre.

Since the mechanical strength of most plastics is low it is desirable, in designing an insulator made from them, to use some reinforcement, such as glass fibre, to keep the size reasonably small. Polyester, epoxy and silicone resins are suitable for use with glass fibre and they also have good electrical properties and resistance to chemical corrosion. Polyester resin is considerably cheaper than the others, and was used in the trials described, except in one case where epoxy resin was used.

The insulators were of very simple form, consisting of resin-bonded glass-fibre rods of $\frac{3}{4}$–2 in diameter and 3–4 ft in length, with metal 'sheds' spaced about 9 in. Seven such insulators were life-tested at a voltage of 85 kV, and failure occurred in periods varying from 10 days to 7 months. In most cases failure took the form of severe surface tracking or internal breakdown along the glass fibres, and there was evidence that unsuitable fillers or incomplete impregnation and curing were responsible.

In one insulator, which flashed over in seven months, shrinkage of resin from the glass was thought to have occurred, with consequent moisture ingress. There was also spark erosion but no tracking. An epoxy resin insulator remained on test for three months but flashed over during foggy weather, presumably owing to its short leakage path of only 36 in. There was no sign of erosion or tracking.

From the results of these initial trials it was concluded that, for insulators of this type to be successful, in addition to improvements in the material, better weather protection is needed and either a much longer leakage path or some resistive voltage control should be provided. The key to improvement in the material is the achievement of a strong resin-glass bond, and amongst the various steps that can be taken to this end are the use of a low-shrinkage resin (epoxy is better than the polyester resin in this respect), and appropriate fibre treatment, including size removal by chemical means and pre-heating to remove the water film before impregnation. Vacuum impregnation is also essential, but too low a pressure must be avoided to prevent boiling off the catalyst or accelerator.

(3.5) Insulator Cleaning

In polluted conditions it is common to add one unit to the line and busbar insulators normally used. In general, however, it is impractical and uneconomic to increase the insulation still further to deal with unusually bad conditions; regular cleaning may then be necessary. This may be done by hand, when conditions permit frequent access. When this is not possible live-washing may be adopted. A somewhat different type of cleaning is used to renovate rather old insulators which have collected a tenacious coating of dirt.

(3.5.1) Hand Cleaning.

The efficacy of hand cleaning has long been established, and it is carried out regularly in many badly polluted substations and on overhead lines. The interval between cleanings may

need to be as short as a fortnight during the winter. In some cases, however, the operation may be carried out only once or twice per year. The frequency of cleaning can best be determined from the local site conditions, preferably with the aid of a leakage-surge counter and milliammeter installed on representative insulators in the substation.

The cleaning operation usually consists in wiping off the deposit with a wet or paraffin-soaked cloth followed by a dry one. There is some evidence that a final wipe with a cloth soaked in transformer oil is effective.

An example of the results that can be achieved with hand cleaning is provided by the special case of the 250 kV test transformer at Croydon. The high-voltage anti-fog bushing has a leakage path of only 132 in, and yet no trouble has been experienced although it is continuously energized at 231 kV. This is achieved by cleaning weekly throughout most of the year. Further examples of the efficacy of cleaning 275 kV 8-unit pedestal posts are given in Section 4.2 and Fig. 8.

(3.5.2) **Chemical Cleaning.**

When it is desired to remove the very hard dirt layers that form on an insulator after many years' exposure in a dirty area, chemical methods must be used. Methods of cleaning were investigated, and techniques developed for dealing effectively with the most tenacious deposits on suspension insulators. It was shown that immersion of the insulator in a 2% solution of caustic soda with 1% Teepol would completely remove such deposits. The period of immersion required is 20 min at a temperature of 100° C or 45 min at a temperature of 60° C. An investigation was made into the possible harmful effects of such treatment. It was shown that, in a sample of some 200 insulators, no significant change in the mechanical strength was brought about by the treatment, but the puncture strength was slightly reduced, particularly with the longer immersion at 60° C.

It should be observed that the type of deposits under discussion usually take a very long time to build up, and, furthermore, considerable deterioration of the metalwork may be involved. Thus a complete reconditioning is required if the insulators are to be re-used. In weighing the cost of this against new replacements, consideration should be given to the effects on line security of the use of old insulators, as opposed to new insulators probably of more advanced design.

(3.5.3) **Live-Washing.**

Where it is difficult to obtain access to substation insulation for hand-cleaning as often as conditions demand, live-washing may be used. This is quite an effective process and is still widely employed. Certain well-established conditions[12] regarding water resistivity and safe distances have to be satisfied.

Considerable service experience is available as a guide to the necessary frequency of the operation, and the surge counter may by used (see Section 3.5.1). However, flashovers may actually be initiated by live-washing if the insulators have been allowed to collect too much dirt. Consequently the frequency of washing is important, and an investigation on this was made at Croydon.

Four 11-unit standard-disc suspension insulator strings were employed for the investigation. Three of these were at low level (ground clearance of approximately 20 ft) and one was at high level (ground clearance of approximately 45 ft). Of the three low-level strings one was left unwashed as a control, one was washed for the greater part of the investigation using the mains pressure of 70 lb/in^2 and one was washed using a pressure of 180 lb/in^2 from a motor-driven centrifugal pump. The high-level string could only be reached with the higher-pressure delivery. A standard washing time of approximately $\frac{1}{2}$ min per

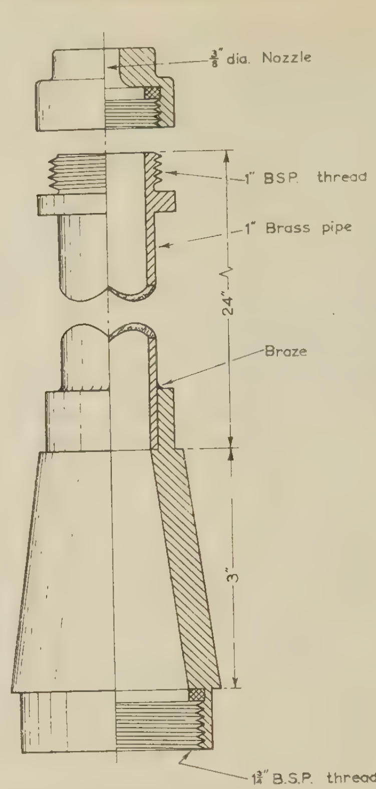

Fig. 7.—Nozzle design for live-washing.

string was used throughout. Initially a standard branch with $\frac{1}{2}$ in jet was employed, but a $\frac{3}{8}$ in jet of special design (Fig. 7) was developed and used for the latter half of the investigation, in order to reduce the amount of water used and increase the carrying power.

The results of the experiment, which lasted 60 months with washing at intervals of one to four weeks, may be summarized as follows:

	No. of surges during washings	*No. of surges between washings*
Control	—	1 250
Low level (mains) ..	228	12
Low level (pump) ..	170	40
High level (pump) ..	175	925

The following conclusions can be drawn:

For insulators at low level, a good performance can be obtained with fortnightly washing during the winter and monthly during the summer, using a pressure of 70 lb/in^2 with a $\frac{1}{2}$ in or $\frac{3}{8}$ in jet.

A pressure of 180 lb/in^2 is barely sufficient for insulators at high level to be washed from the ground, with either of the above jets, and even weekly washing is not very effective.

It should be possible by using a higher pressure to produce an effective jet for washing high-level insulators. However, the attainment of the pressures involved,[13] about 600 lb/in^2, requires reciprocating pumps and armoured hose, and, generally, a somewhat specialized installation.

(4) INSULATORS FOR 275 AND 380 kV

(4.1) Insulators for 275 kV

Several years' experience of 275 kV insulators has been obtained using a voltage to earth of 175 kV. The work had to be terminated on 16th September, 1955, so that investigations

on the behaviour of 380 kV insulators could be started, but several of the insulators that had been undergoing test at 175 kV were re-energized at 231 kV to gain further information about them. Table 4 summarizes the results obtained at both 175 and 231 kV.

Three designs of pedestal post (Fig. 3, Nos. 3, 4 and 5) were among the first insulators to be tested. The number of leakage surges recorded by these insulators is shown in Fig. 8, and the marked difference in results for insulators with only slight variations in design can be seen. The insulators were erected at intervals of a few months, and this has had some influence on the total surge counts. However, after less than a year, when the insulators are thoroughly dirty, the rate of surge counting can be expected to be independent of the time they have been energized. Only one of the three posts counted no surges at 175 kV, and this was also the only one not to flash over at 231 kV.

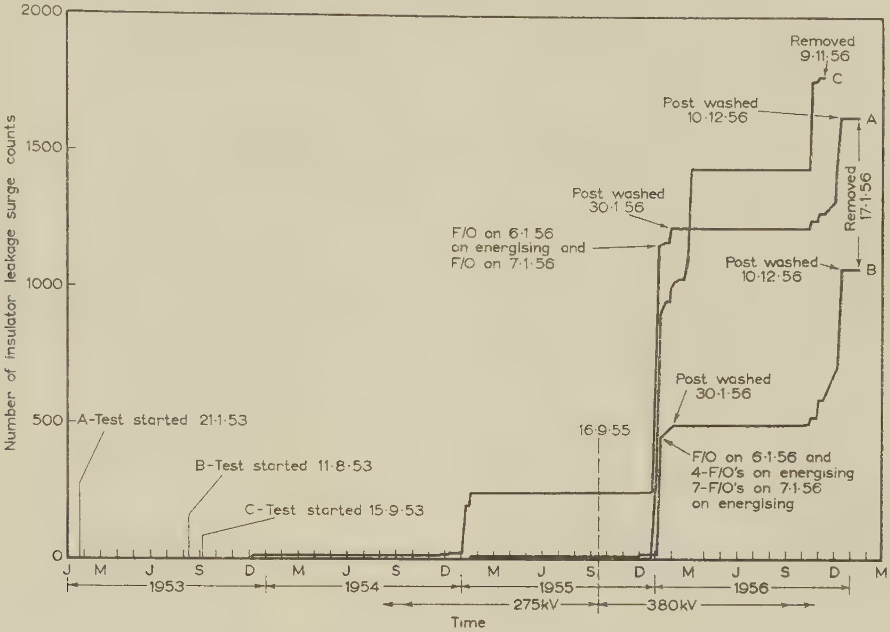

Fig. 8.—Performance of 275 kV 8-unit post insulators.

A.—Fig. 3, No. 3.
B.—Fig. 3, No. 4.
C.—Fig. 3, No. 5.

The 275 kV current-transformer bushing (Fig. 3, No. 2) is satisfactory, but compares unfavourably with a 132 kV current-transformer bushing of the same manufacture, although both have anti-fog sheds and almost the same leakage path per kilovolt of system voltage. The 132 kV bushing recorded 36 surges up to 16th September, 1955, and the 275 kV bushing 115, although the lower-voltage bushing had then been on test 45 months, and the other 21 months only.

The duration of the test at 175 kV was insufficient to give worthwhile results on the effectiveness of the suspension insulators, and longer strings of the same designs were accordingly put on test when the voltage was raised to 231 kV.

(4.2) Insulators for 380 kV

The investigations which have been carried out with insulators designed for the proposed 380 kV system have been in progress since 30th September, 1955, and the results have been included up to 31st March, 1958.

Two of the requirements for suspension insulators for this voltage are that they should have an electro-mechanical strength of 30 000 lb and that the insulator with its fittings and cross-arm shackle assembly should not exceed 150 in in length. An allowance must be made for the fittings, and accordingly the lengths (measured from the ball at one end to the socket at the other) of the prototypes for test were chosen with this in mind. Probably the most onerous of the other technical requirements is that the insulator shall operate in polluted atmospheres without flashover.

At present, all the design requirements for 380 kV isolator posts have not been decided, but it is hoped that these posts can be made identical with the busbar supports. Since the horizontal load on the isolator and the height will be greater than for a 275 kV design, the mechanical rigidity must be increased. To meet this requirement various types of post have been suggested. They include pedestal types having about ten large units; cylindrical or tapering types composed of two or more units; a tripod of multi-unit rod insulators and an arrangement of 275 kV pedestal post units in an 'inverted Y' (see Fig. 3, No. 9) which has greater mechanical rigidity in the plane of the insulator centre lines. Examples of all these types except the tripod insulator are undergoing examination at Croydon.

Another problem, which is more difficult with pedestal than cylindrical posts, is that of obtaining an adequate corona-inception voltage. The line unit of a single stack of pedestal units may carry 25% of the total voltage due to the effect of stray capacitance. With an arrangement such as the 'inverted Y' post the distribution will be even worse. To increase the corona-inception voltage the top two units of a 10-unit pedestal post have been coated with a fringe of semiconducting glaze on the porcelain around the caps.

Details of the performance and physical characteristics of most of the insulators which have been energized at 231 kV are given in Table 4. Those insulators which have been tested at 175 and 231 kV, as might be expected, gave an inferior performance at the higher voltage.

Fig. 9 shows typical leakage currents for several 380 kV insulators during rain. The relatively steady current of the greased and oil-filled insulators is characteristic of these types,

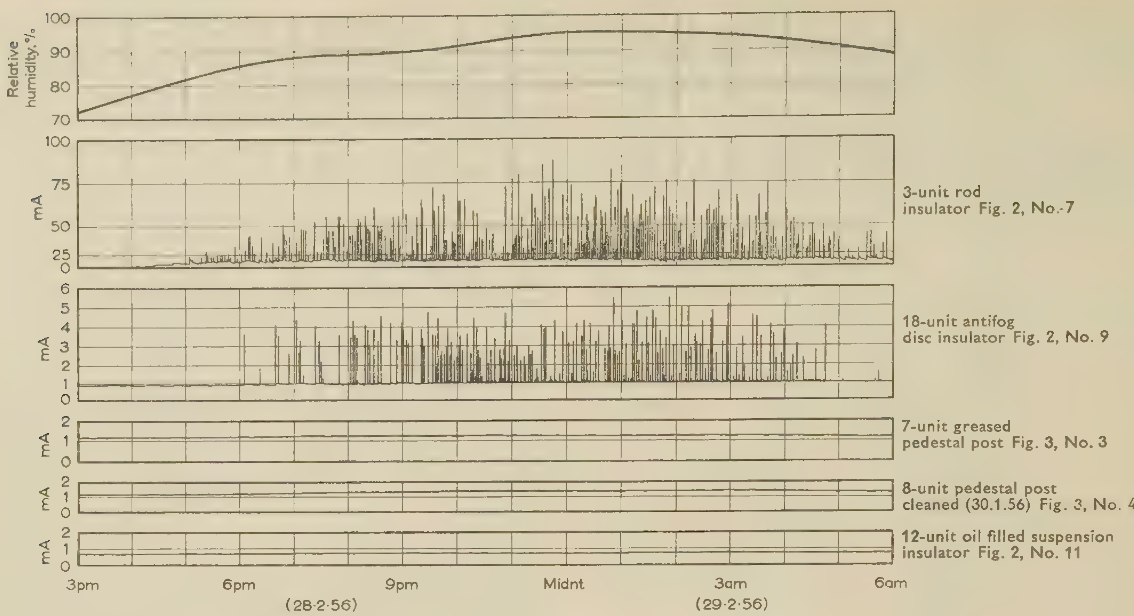

Fig. 9.—Leakage currents for 380 kV insulators during rain.

but the particularly good performance of the 8-unit post insulator was due to cleaning four weeks previously.

The record of the performances of the three 8-unit pedestal posts at 231 kV (Fig. 8) provides a striking comparison. This also shows the beneficial effects of cleaning; without the cleaning of two of the insulators it is almost certain that more flashovers would have taken place.

Of those post insulators especially designed or assembled for 380 kV, the 'inverted Y' design (Fig. 3, No. 9) has already flashed over. The others have not had a long enough test period for proper assessment, but the 4-unit cylindrical post (Fig. 3, No. 8) has not given as good a performance as the 10-unit pedestal and the 2-unit cylindrical posts.

The semiconducting glaze fringe on the 10-unit pedestal post showed excessive corrosion after one year, showing that the current involved is comparable with that of a stabilized insulator. Insulator units with glazes having lower corrosion rates have now been substituted for the original units.

The new designs of porcelain anti-fog suspension insulators are of great practical interest, since the use of the oil-bath and greased insulators is only likely to be contemplated in the most heavily polluted areas. The designs which have been under review for three winters are an improvement on the insulator made up of 132 kV anti-fog units with a similar leakage path length which has flashed over (Fig. 10).

The performances of the 380 kV anti-fog insulators (Fig. 2, Nos. 9 and 14) are considered to be fairly satisfactory. Both insulators first tested were slightly too long, but it should be possible to effect a reduction of a few inches in overall length, without detriment to performance, by small design changes.

(5) RESULTS OF D.C. INVESTIGATIONS

Arising in the first place from the decision to use a d.c. system for the interconnection between the British and French systems, research on the performance of outdoor insulation for high-voltage d.c. operation has been put in hand.

Very little information on this question is available from other countries, and what little there is[14, 15] does not suggest that the insulation at 100 kV d.c. constitutes a very serious problem under the conditions which applied. This would not

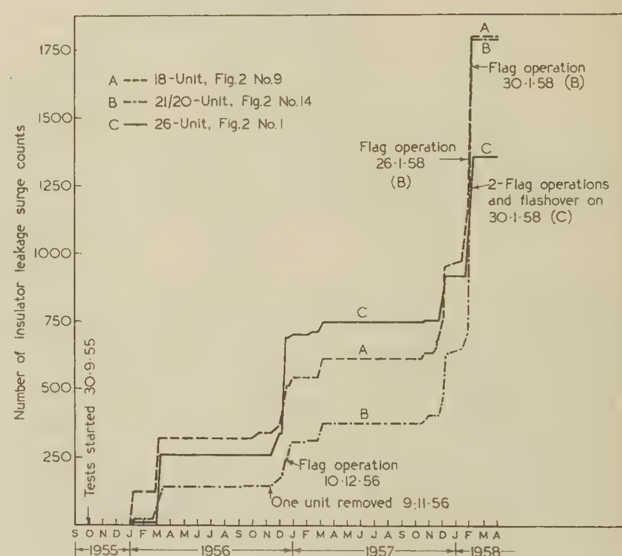

Fig. 10.—Performance of 380 kV anti-fog suspension insulators.

necessarily be the case, however, under British conditions, with the relatively high incidence of high humidity and fogs together with industrial or saline pollution.

Preliminary tests were started at Leatherhead in May, 1956, when a voltage of 140 kV d.c. negative polarity was applied to two anti-fog suspension-insulator strings, one of seven and one of ten units, and a bushing. The figure of 140 kV was chosen as the highest available from existing plant. At the time, both 100 and 200 kV were under consideration as possible transmission voltages. These tests were followed by life tests at Croydon, started in January, 1957, using 115 kV d.c. also of negative polarity.

The testing technique adopted for d.c. systems was the same as that used for a.c. systems, except that the corresponding d.c. instruments were used. For surge recording, the type of counter employed for a.c. tests was used but its sensitivity on direct current is higher, the minimum operating current being 13 mA.

All counters for direct current at Croydon were adjusted in January, 1958, to operate at 25 mA. The flag indicators operate at 150 mA.

The current rating of the supply at Leatherhead was 100 mA, and an output capacitance of $0 \cdot 16 \mu F$ was used. The corresponding details for the tests at Croydon are given in Section 2.

(5.1) Clean Atmospheres: Leatherhead

Conditions at Leatherhead are not onerous from the insulation point of view, and yet, despite this, minor surges of just over 1 mA were recorded within a few days, surges of several mA occurred within two months and the first counter operations in just under six months from the start of the tests. There was a count of six surges on the 7-unit string on this occasion, and this rose to 322 a few days later when three surges were recorded on the 10-unit string also. Typical records from these early investigations are shown in Fig. 11.

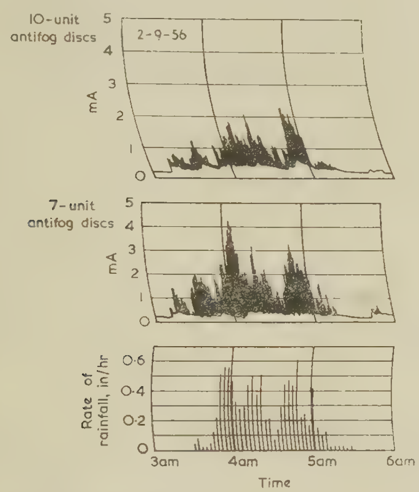

Fig. 11.—140 kV d.c. insulator leakage currents at Leatherhead.

Tests at 140 kV were terminated after a total time of energization of 1 900 hours (exposure time of 7 months), and the voltage was then reduced to 100 kV, which is the normal working voltage to earth of the cross-Channel connection.

During a further 1 000 hours' energization in January and February, 1957, at Leatherhead, there were no surge-counter operations and only minor surges were recorded.

A brief trial of 200 hours' energization with reversed polarity (i.e. 100 kV positive) has since been made, and in the course of this, seven surges were counted on the 7-unit string during rain.

Throughout all the trials at Leatherhead the leakage current was exceedingly low—less than $0 \cdot 1$ mA in fair weather, rising to values of about $0 \cdot 5$ mA between surges during rain.

(5.2) Polluted Atmospheres: Croydon

Investigations were started at Croydon in January, 1957, when the following insulators were energized at 115 kV negative polarity:

An 11-unit standard disc suspension string in very dirty condition.
A 10-unit and a 7-unit anti-fog suspension string.
A 3-unit post.

The performance of the two anti-fog units in the first three months of test did not differ appreciably from that observed over a similar period at Leatherhead, but a very high rate of surging occurred from the outset on the dirty string, 150 (13 mA) surges being counted after four days and 1 500 after four weeks.

In October, 1958, three further insulators were put on test, and details of these together with those already mentioned, and their performances, are given in Table 5 which covers the period up to 31st March, 1959. These insulators were subjected to unusually severe conditions during the winter of 1958–59, which was abnormally foggy.

Observations arising from the tests are as follows:

Polarity effects do not appear to be very marked.

The d.c. electric field associated with the insulators produces electrostatic precipitation of air-borne dust on all adjacent surfaces at or near earth potential. This is the dominating effect in determining the *initial* dirt distribution, but in a few weeks' time, normal weathering processes, dirt deposition by air currents and redistribution of the stress brought about by the deposits themselves result in a nearly uniform dirt distribution.[15]

Grease coating has, up to the present, been found very effective.

Leakage-current surges occur with direct current, as with alternating current. Generally, the behaviour supports the view that the predominating factors in insulator performance are the surface-layer heating and dry-band formation. Thus leakage-surge extinction occurs in much the same times, the drying-out mechanism apparently only being affected to a small

Table 5

Performance of Insulators at 115 kV D.C. Negative

Insulator type	Fig.	No.	Leakage path	Date of energizing	Months of test or to first flashover	No. of surges to flashover or during test: 13 mA*	No. of surges to flashover or during test: 25 mA	No. of flag operations before flashover
			in					
11-unit standard disc	2	6	135	17th January, 1957	23 (F.O.)	8 391	7 563	5
10-unit anti-fog disc	2	1	167½	24th January, 1957	26	507	2 698	1
7-unit anti-fog disc	2	1	117	24th January, 1957	22 (F.O.)	3 860	4 112	12
3-unit post	4	6	89	28th January, 1957	12 (F.O.)	15 346	3 487	3
4-unit post	4	6	119	10th October, 1958	6	—	4 969	4
5-unit post	4	6	149	10th October, 1958	6	—	1 849	6
Bushing, standard sheds	—	—	92	10th October, 1958	2 (F.O.)	—	753	0
Bushing, standard sheds (greased)	—	—	92	11th December, 1958	4	—	2	0
10-unit glass anti-fog disc	2	13	145	11th December, 1958	4	—	340	0
7-unit anti-fog disc (greased)	2	1	117	11th December, 1958	4	—	0	0

* Before counters adjusted to 25 mA operations in January, 1958.
F.O.: Flashover.

extent by the absence of voltage and current zeros. It must be borne in mind, however, that the ripple of the test voltage will increase during high-current surges. For example, with a current of 150 mA the voltage drops to 90 kV with a ripple amplitude of 12 kV peak-to-peak.

On the basis of this experience the insulation required for 110 kV d.c. in polluted atmospheres cannot be specified with certainty, but it is clear that at least 10 anti-fog units will be essential and probably 13 units will be required to ensure satisfactory service performance. This corresponds to approximately 1·5 and 2·0 in of leakage path per kilovolt of applied voltage, which may be compared with the normal practice for 132 kV line insulators of 1·56 in/kV (peak) of applied voltage (1·26 in/kV between phases) for alternating current.

(5.3) Corrosion

It was expected that the corrosion of the metal fittings of an insulator, which occurs in polluted atmospheres, would tend to be enhanced, as a result of electrolysis caused by the leakage direct current.[14] The effect is also present with leakage alternating currents, but to a very much smaller extent. The most severe corrosion is to be expected at the pin of a cap-and-pin unit, where current is transferred from the porcelain surface via the cement. Accordingly, careful inspections have been made of the units involved in the above tests. Up to the present, no appreciable corrosion has occurred.

(6) ARTIFICIAL SALT-POLLUTION TEST

Many attempts have been made to develop a satisfactory artificial pollution test, but great difficulties have been experienced in satisfactorily reproducing service conditions. It is necessary to build up the surface deposit as in service, with the normal working voltage applied to the insulator. In addition, the performance of the insulator must be assessed at the normal working voltage. Observations made by increasing the voltage until flashover occurs can be misleading, as it takes a considerable time for the conducting surface layer to reach equilibrium for a given applied voltage and atmospheric humidity.

The surface layer produced by industrial pollution is particularly difficult to reproduce for the reasons given above, but salt pollution can be more easily simulated by the method described in Section 2.

Investigations made using a bushing and 3- and 4-unit pedestal posts at 85 kV indicate that the severity of this test method is roughly equivalent to a long-duration test at Croydon. For example, the bushing (Fig. 4, No. 5; leakage path 116 in) did not flash over after several hours but the 3-unit post insulators (Fig. 4, Nos. 6 and 7; leakage paths 89 and 97 in respectively) did flash over.

A rapid build-up of salt deposit was observed when the bushing was tested. As the insulator was being sprayed, dry bands of crystalline salt formed between the sheds, starting at the narrower upper end, while, at the same time, the current surges were gradually increasing in amplitude but decreasing in frequency (Fig. 12).

This behaviour conforms to the mechanism of flashover previously described.[3] The dry bands are the areas of maximum resistance, and when they spark over, the resistance of the wet part of the surface limits the surge current. The arc is generally self-extinguishing, but if the current is too great, flashover will occur (Fig. 13). According to experiments by Frischmann,[16] the arc roots travel back across the wet surface without drying off more than a small part of it, thus increasing the current and lengthening the arc until complete flashover occurs.

Dry salt bands were not observed when the pedestal-type insulators were tested. This may be due to the fact that the salt spray does not penetrate to the innermost parts of the sheds, which are dry from the start of the test.

A comparison has been made between the behaviour of greased and ungreased insulators in salt spray. The 3-unit pedestal posts of both types flashed over within two hours at 85 kV but did not flash over when freshly coated with grease. Moreover, under the same test conditions, 3-unit posts which had been coated with the same grease and in service for a year, did not flash over.

Weather conditions, especially wind speed and direction, affect the results with the apparatus described and a new arrangement has now been made, similar to a short wind tunnel,* which should give more repeatable results and form the basis of a realistic test. In addition, a new testing station has been established on the coast at Southwick (Brighton), and arrangements are being made to study the performance of a.c. and d.c.

* It is interesting that a wind tunnel was used by Prof. W. J. John many years ago in studying the deposition of salt on insulators.

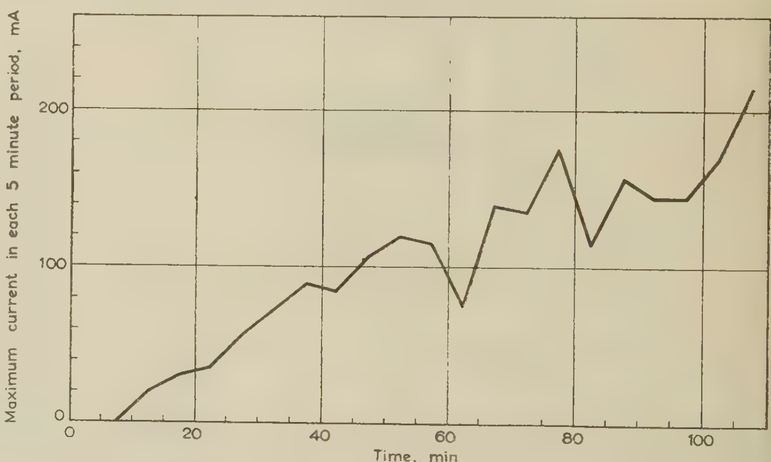

Fig. 12.—Leakage current of a bushing on artificial salt spray test.

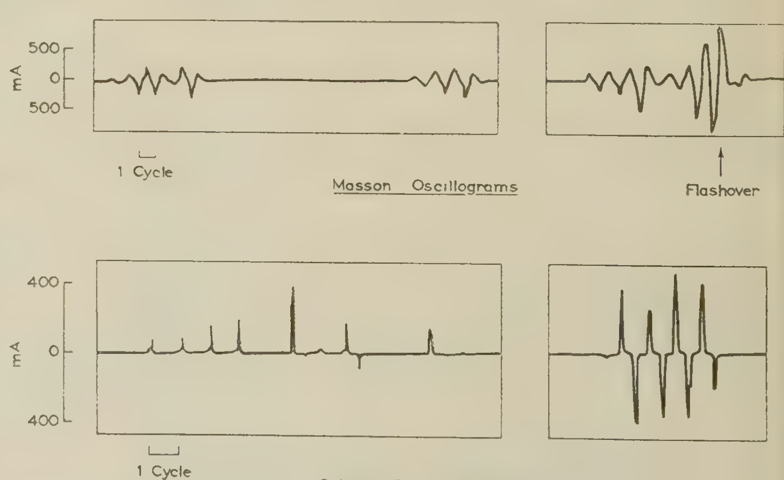

Fig. 13.—Oscillograms of leakage-current surges taken during artificial salt spray tests.

insulators at this site in order to provide comparative results under actual service conditions.

(7) CONCLUSIONS

Measurements on various types of insulator have confirmed that the leakage path length is the main factor in determining insulator performance in polluted atmospheres. The configuration of the leakage path must be carefully designed to provide a good proportion, about one half, of protected surface and to avoid too closely-spaced deep corrugations or sheds. With this proviso, the figure of merit of an insulator can be taken as the ratio of the length of the leakage path to the overall length of the insulator. This ratio should be about 3 for an anti-fog suspension insulator.

Insulators designed for 380 kV have been operated at this voltage in polluted atmospheres at Croydon for three years, and such designs could be used for 380 kV lines in this country. The difficulties of operation at these voltages in very polluted atmospheres should not be under-estimated, however, and with the decrease in general industrial pollution, and the siting of more generating stations near the coast, trouble due to salt deposits is likely to become relatively more important.

Insulators of various types have been tested at 115 kV d.c. in polluted atmospheres and it appears that about 30% more insulation is required for high-voltage direct current than for alternating current of the same peak voltage.

Greasing of the insulator surfaces has been shown to be very effective, and this palliative is being used to a considerable extent in difficult conditions.

Progress has been made in understanding the behaviour of semiconducting glazes, and improved glazes are being developed.

The search for new materials for outdoor insulators continues, but so far no substitutes for porcelain or glass have been found.

The testing technique developed over 20 years ago has withstood the test of time, but difficulties are encountered in obtaining a precise measure of insulator performance. It is not easy to assess the relative performance of insulators which differ only slightly. However, significant differences in performance are easily determined.

Promising results have been obtained with an artificial salt-pollution test, and further development of this technique is in progress.

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DISCUSSION BEFORE THE SUPPLY SECTION, 18TH NOVEMBER, 1959

Mr. P. J. Ryle: This paper, together with Dr. Forrest's earlier papers on the same subject, undoubtedly make history, but, from the References, history seems to go back only to 1934. Pre-history, a field largely of surmise and speculation, is a category clearly appropriate to my 1931 paper,* which described North-

* Ryle, P. J.: 'Two Transmission Line Problems', *Journal I.E.E.*, 1931, **69**, p. 805.

East-Coast experience on 66kV lines and some early attacks on the insulator pollution problem. My comments on the present paper relate chiefly to overhead-line matters.

I am rather surprised that in 1951–55 appreciably more faults per 100 year-miles were attributed to salt than to ordinary industrial pollution. Is this representative of general Grid operating history to date?

A subject not touched on by the authors is the effect of snow. We do not hear of high fault rates on lines in severe snowstorms, although melting chunks of snow must present almost direct water paths across the insulators.

Grease application appears promising, but the thick coatings shown in the laboratory to be desirable would be very difficult to apply satisfactorily in service. Grooves, pockets and bare patches in the grease inadvertently left by linesmen or caused by heavy rain or hail might invite dangerous water and dirt concentrations. Would the sticky surface of the grease encourage the adherence of straw, leaves, etc., and possibly of long dew-drop-covered threads of gossamer such as may conceivably be associated with 'early-morning' faults?

On the subject of voltage distribution, I should like to know whether attempts have ever been made to produce a semiconducting insulator body material (whether ceramic, glass or something else) which might equably divide the voltage over the units, although distribution of voltage over the insulator surfaces themselves would probably be inferior to that afforded by semiconducting glaze. Do the authors share my view that semiconducting glaze (or the equivalent) is likely to be just as desirable for d.c. as for a.c. systems?

With d.c. systems, the authors adumbrate no great polarity effects on deposit collection. Is this to be regarded as independent of the type of particle concerned, e.g. smoke, fly-ash, very fine water drops, cement dust, pollen, etc.?

The paper contains very little information about the well established superiority of tension insulator performance. Have any experiments been made to see how far the number of units in a tension string could be reduced before its surge count and general behaviour approximated to those of a suspension string under the same bad conditions? Very exceptionally, tension strings behave worse than suspension strings. Some years ago in north-east Scotland a heavy easterly gale carried so much salt that car windscreens facing eastwards were completely obscured, and a 132kV line flashed over several times, but always at the tension insulators; apparently also the affected strings were those with their corrugated undersides directed generally towards the sea. However, experience is universal that tension-string pollution troubles are relatively very rare. In the past it was traditional (simply with wet flashover in mind) to insert an arbitrary extra unit into every tension string, but I feel that we could nowadays seriously consider actually reducing tension-insulator string lengths. This suggestion might receive the disapprobation of insulator manufacturers, who could justifiably retaliate with a technically sound proposal—that of using tension insulators at all towers, thus approximately doubling their potential market at one blow!

We hope that within the next ten years the authors will produce another paper giving extended experimental and service results at 275kV, 380kV and possibly even higher voltages a.c., and at correspondingly high voltages d.c.

Monsieur G. Leroy (*France*): I believe that three successive stages must be considered in order to choose an insulator design to cope with specified pollution. The first is the line test stage, which can be carried out by equipping the three phases of a line passing through an area of given pollution with different designs of insulator. The annual number of flashovers in each phase is noted. Reliable conclusions can be drawn, with the test made on insulators under the normal operating condition. Unfortunately, the test takes a long time and is, of course, limited to three designs. It can be therefore applied only in a very small number of cases, e.g. to select one design among three which differ only slightly or just before the generalization of a particular design for a given type of pollution.

The second is the station test stage with natural pollution. The conditions under which the tests take place are as natural as in the preceding case, but a large number of different insulator types can be tested at the same time. Fresh difficulties arise, however, in the interpretation of the results. The operator has no control over the test conditions. He has only two possibilities after the choice of the test area: to measure the time to flashover under normal operating conditions (but with a correct design stage a flashover is relatively rare), or to measure the leakage current; but there is no close connection between leakage-current characteristics, peak value and repetition frequency and flashover under normal conditions. Further, the classification thus obtained is probably incorrect and cannot be considered sufficiently reliable to be used entirely without plant tests. This is the opinion of one of my colleagues who carried out this sort of station test in an area subject to industrial pollution.

The third is the laboratory test stage. The operator has control over the test conditions and can base his conclusion on the time to flashover. The objections to the second case no longer apply, but others arise from doubt about the true nature of the polluted layer. These tests are quickly carried out, as compared with the preceding ones, but they are not sufficiently reliable to use alone. Therefore, for design tests, they can be used only in the progressive study and adjustment of new designs for which numerous alternatives are necessary, while for the system engineer these tests are limited to acceptance tests, considered, however, as type tests. When a few shapes have been chosen by such artificial results, it seems necessary to pursue tests under natural pollution conditions before beginning construction.

These three stages follow successively, and it seems very important to continue research simultaneously on all three. I should like to know whether this is also the authors' opinion, and whether they consider that the results obtained at the Croydon testing station must be checked in the field.

The artificial salt-pollution test described in the paper is simply for studying the seaside problem, but it seems that the authors intend to use it for the study of industrial pollution. I am afraid that the method is not well adapted for dealing with the industrial problem. It is very important to reproduce the washing action of the rain. This condition prescribes the use of a solid dirt deposit instead of a liquid. We have used a method which consists in spraying the surface of clean insulators with a very fine spray of water with a low resistivity. The best method might be to use solid dust deposited on the insulator followed by a few minutes of artificial rain.

Mr. J. A. Broughall: British Railways are very keenly interested in this question of insulator design and pollution, especially since we have adopted the high-voltage a.c. type of electrification.

We encounter worse pollution than anyone. Not only do we experience in industrial districts the pollution common to everyone, but steam locomotives are themselves one of the major sources of pollution, and thus we give ourselves difficulties by causing this pollution underneath some of the insulators.

We have dealt with the problem in two ways. First, we try to have these experimental lines energized as early as possible before they are put into public service. In one case, however, in order to make a profit out of the electrification, the line was put into public service two months after it was energized.

However, we are gradually accumulating experience to show whether we were correct in our estimate of what was the right kind of insulator to use for this work, because, added to the fact that there is an extraordinary amount of pollution, we have almost no facilities for getting at the insulators to clean them. I am referring to the main lines, where the intervals between trains are rarely sufficient for a man to climb up to the insulators, let alone giving him time to do something when he gets there. We have therefore adopted a generous creepage distance, and, so far, we do not seem to have been too far out. We have almost doubled the creepage distance which the French railways use for the same purpose, and I think that our climate is at least twice as bad as theirs. This represents one line of approach.

With the assistance of an industrial research organization we have had in service for nearly three years a test gantry by which we have simulated fairly well rather worse conditions than the worst which we set up ourselves. We have put a large number of insulators of different types dead over the track and the funnels of the many steam locomotives which use that section of line. We have got some extraordinarily dirty insulators and have been able to grade them after a fashion.

I understand that a Japanese research organization have found that cleaning by a portable steam generator is very satisfactory. Have the authors considered this idea?

Mr. E. F. Johnston: Several insulator testing stations are now working on what could be called the Croydon principle, using the techniques which the authors have devised. I wonder whether any attempt has been made to correlate the results obtained at these different stations and thus make available a very much greater volume of test experience. Before a comparison can be made, the relative importance of the different factors which affect the results obtained at different stations must be assessed.

I am concerned with a similar testing station where the monthly deposit is between 20 and 25 tons per square-mile, which is less than one third of the Croydon figure. On the other hand, the atmosphere is very much more acid. The amount of sulphur trioxide recorded is 6 mg per 100 cm^2 per day, i.e. approximately $2\frac{1}{2}$ times the value quoted for Croydon. I suggest that the acidity of the atmosphere has a greater bearing on the surge counts which will be recorded than the weight of deposit, provided that there is sufficient dirt to put a really good coating on the insulators fairly quickly.

I am of the opinion that data on atmospheric conditions are of limited value and that an accurate correlation between the results from different stations may be obtained by comparing the performance of like strings under test in each of the different stations. A 14-unit string of high-capacitance anti-fog insulators, similar to those referred to in Table 4, is installed in the station to which I referred and has been energized at 160 kV (equivalent to 275 kV nominal system voltage) for 11 months. The number of 20 mA surge counts recorded is 70. This string is comparable to that of 19 units referred to in Table 4, energized at 231 kV for 16 months for which fifteen 25 mA counts have been recorded. It would seem that the conditions obtaining in this station are more severe than those at Croydon, and I would welcome the authors' views on this conclusion.

Recorders to count surges of 10, 20, 40 and 80 mA, in addition to the 150 mA relay, have been installed at this testing station. The 10 mA count may be a mistake, but I am inclined to believe from the experience so far obtained that the examination of 40 and 80 mA counts may give a rather more accurate comparison between similar designs than would be possible if records of 25 and 150 mA counts only were available.

With regard to the insulator shapes shown in Fig. 2, shapes Nos. 2, 3 and 4 are so similar to shape No. 1 that the dispositions of leakage paths, field strengths and distribution must be closely similar in all cases. I would be glad if the authors state, therefore, why the results from Nos. 2, 3 and 4 are so different from those from No. 1?

Mr. D. M. Cherry: Dr. Forrest deserves well of the industry for his 25 years' work in this difficult field. My only regret is that, for reasons beyond his control, the scale of the work is far too small for the problem. Many more insulators in number and variety should be tested to give a reliable guide as to the best line of development for higher voltages. For example, we need to know now whether, for a 400 kV station, the traditional type of unit post should be further developed, or whether the cylindrical hollow post, more rigid, with better corona characteristics and probably more expensive, should be developed.

Of the new developments, greasing and, for similar reasons, oiling must be regarded as palliatives only. The cost and difficulty of the necessary removal and replacement of grease every two years is too high. The high-capacitance glass unit for lines shows promise. Semiconducting glazes are probably the most hopeful prospect if the known difficulties of self-electrolysis and lack of uniformity in production can be overcome. Unless these developments can be expedited, the best proposition for substations is to site them indoors, which, by careful attention to design, can be done at a very modest premium over outdoor construction.

It must be emphasized that anti-fog insulators, good as they are, do not remove the necessity for cleaning; they only lengthen the intervals between cleaning. As the operational cost of outages for this work at 275 kV is very high, live-washing at 275 kV must be made a practical proposition.

Mr. N. G. Simpson: The following experience with silicone grease on oversea lines supplements data in the paper:

Aden	33 kV	pin insulators	(BS.110 rating, 37 in leakage path)
Karachi	66 kV	suspension insulators	(Five 10 in × $5\frac{3}{4}$ in glass anti-fog $72\frac{1}{2}$ in leakage path)

Both lines lie close to the seashore, with severe sand and saline deposits, little rain except in the monsoon period at Karachi, and high night humidity. There were persistent nightly outages on the Aden line a few weeks after commissioning in 1956, and similar conditions prevailed on the Karachi line in 1957, but with less frequent outages. Insulator cleaning gave temporary relief from shut downs in each case. A hand-applied 10% silicone-grease carbon-tetrachloride solution on the Aden insulators gave 12 months' freedom from shut down, the grease remaining stable at high temperatures. There were no faults after recleaning and treatment. A 30% silicone-grease solution at Karachi in 1958 gave 12 months' freedom from outages with some subsequent outages. There will be retreatment with a higher concentration.

Silicone grease was chosen for stability under tropical conditions. The higher material cost over petroleum grease recedes in relation to dilution, thin coating, overall cost and value of the expedient compared with alternative and doubtful remedies.

Glass-fibre and moulded-resin insulation appears to sponsor a new departure in transmission-line technique including structural form. Our concept of the possibilities is guided by its character, mode of manufacture, adaptability, insulation and mechanical strength and the scope for control of electrical stress and leakage current. Economic advantages arise in a possible upward shift in the line of demarcation between supporting and suspending conductors at present in the 33–66 kV range.

Below 33 kV, resin material in insulation and supports is not justified except for improved operation in high lightning areas. Above this voltage, cost reductions and improved performance can be progressively important. Fig. A compares a conven-

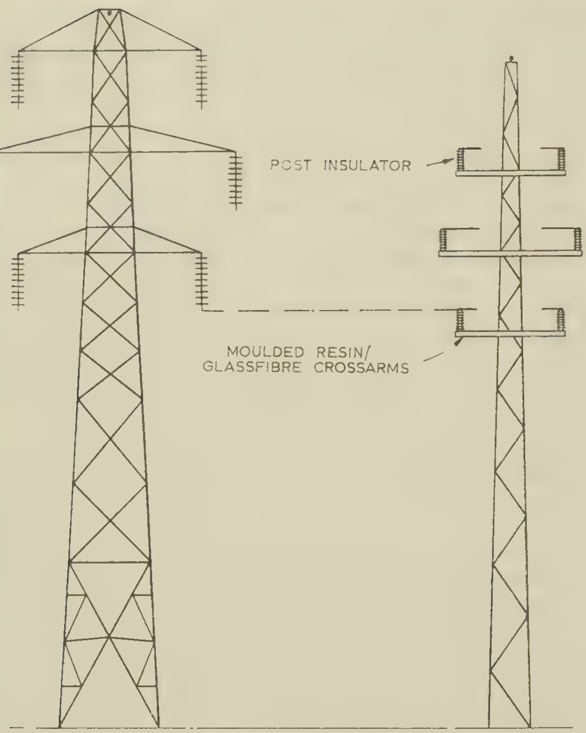

Fig. A

tional 132 kV support with a likely alternative having a post insulator and a moulded-resin supporting crossarm. The insulator contributes a reduction of leakage-current and therefore tracking. The adjustable arcing horn controls impulse level and flashover path (see Fig. B). Ribs break up the continuous moisture film, and the shape has self-cleaning action.

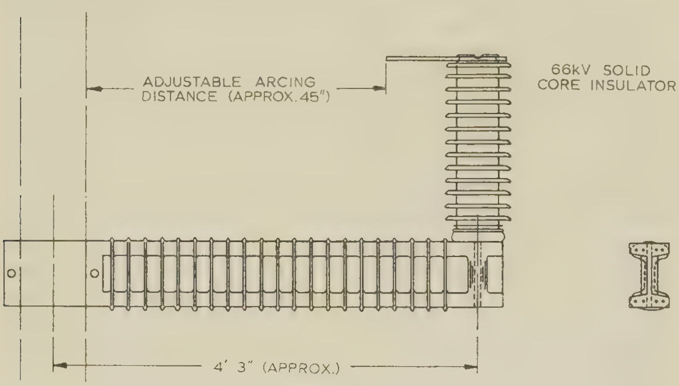

Fig. B

The anti-tracking problem may not be under-estimated, but there is scope for overcoming it. There is a call, oversea, for long inexpensive e.h.v. lines, and such developments are likely to achieve this.

Mr. W. G. Todd: I would like to describe the steps which became necessary at the Littlebrook substation of the C.E.G.B., where greasing of insulators had to be carried out.

Three years ago a flashover across two 5-unit 132 kV post insulators forming part of the busbar system occurred on two successive foggy mornings. On each occasion the whole of the output from Littlebrook power station was lost. Drastic action became necessary, and all the 768 post insulators and the many bushing insulators there were coated by hand with a thick grease.

The type of pollution responsible for the trouble was pulverized-fuel ash from the power station, together with cement dust from factories in the neighbourhood. The grease prevented further flashover, but its regular removal and renewal presented a fresh problem. This could not be done quickly enough by hand to enable half the station to be dealt with each year to ensure that all grease was renewed every two years. Various methods, which included steam cleaning and high-pressure water jets, were tried, but each introduced fresh hazards and had quickly to be abandoned. Finally, it was found that the only satisfactory method was to remove the insulators from their normal position by means of special dismantling equipment and to convey them to some special plant, which had to be designed and constructed, and which would enable them to be dipped while rotating into a hot cleansing solution to remove all dirt and grease. After cooling the same carriage would be used to dip them while rotating into another tank containing hot grease which would enable an even layer of grease to any desired thickness to be applied easily.

Some difficulty was experienced during the recent very hot summer weather due to grease running, but this occurred only on the bushing insulators where the grease had been applied by hand and was therefore less even in thickness.

The measures taken at Littlebrook have been successful. No flashovers have occurred there since grease was applied, although they have occurred on the overhead lines nearby.

It has been said that greasing is only a palliative. If Littlebrook station were being built to-day, the substation would be housed. It would be impossible to do this now, and greasing, although difficult and costly, has made it possible to keep a station in commission at times of the year when this would otherwise have been impossible.

Dr. C. H. W. Clark: The results given in the paper show considerable variability, which makes it difficult to draw firm conclusions. Some sort of statistical analysis on the significance of the results might be useful, and I should like to quote two examples of conclusions drawn by the authors which I feel are not adequately supported.

In Section 3.1.1 they compare the performance of two 6-unit insulator strings. In their conclusions they imply that part of the difference in performance of these two strings is due to the fact that one is made of glass and the other of porcelain. I doubt whether the difference is really significant at all. The variability of this sort of test is illustrated by the results for 10-unit strings of units Nos. 1–4 of Fig. 2. These were tested for only slightly different times, and it is reasonable to compare them on a basis of surges per month. The ratio between highest and lowest surges per month is 15 : 1. Units Nos. 1–4 are very similar in shape, and all are the same size except No. 2, which has a smaller diameter. In comparing Nos. 5 and 1 I detect a more definite difference; the rib under the shed of No. 5 has been exaggerated to such an extent that the length of the insulator is increased. The difference in surges per month for the two 6-unit strings is 1·4 : 1. I suggest that this difference, if it is significant at all, would be more than adequately explained by the difference in size and shape of the two insulators.

As a second example I would refer to Fig. 8 and the comparison of three 275 kV posts. The authors state that 'the marked difference in results for insulators with only slight variations in design can be seen'. It seems to me, on reading further, that this 'marked difference' depends on the assumption that '. . . after less than a year, when the insulators are thoroughly dirty, the rate of surge counting can be expected to be independent of the time they have been energized'. The performance of insulator A is recorded in Fig. 8. In the first year of exposure there were no surges, in the second year there were 20, and in the third year 250. Is this independent of the

time of exposure? The other graphs show the same sort of rising characteristic; the curves certainly do not settle down to a constant slope. Is it correct, therefore, to compare these three insulators without allowing for the different times of exposure?

Dr. F. H. Last: The paper needs to be read in conjunction with the earlier papers by Dr. Forrest and quoted in References 2 and 3. It was shown in the latter paper that the tension insulator string does not present a problem when subjected to industrial pollution, and this is borne out by service experience. The performance is good because the surface becomes uniformly polluted and has a uniform leakage path. This demonstrates that an intentionally applied conducting surface to suspension insulators would result in a greatly improved performance. A satisfactory unit has not yet been produced, and the development of a stable and durable conducting glaze must be encouraged.

The authors state that greasing is only a palliative. Despite the comments of many speakers, in my opinion it is a completely unsatisfactory procedure. The apparent cost of the actual process may be negligible, but the hidden cost resulting from line or substation outage, probably requiring out-of-merit running of generating plant, may be very high, particularly where 275 kV equipment is concerned. It is admitted that greasing may help to solve local problems, but it must not be considered a satisfactory measure to be used on a wide scale.

Mr. G. B. Jackson: I look on this problem purely from the viewpoint of the line design engineer. He is of necessity a very impatient person; he requires results quickly, because he is strictly rationed for time. In the time that he is given to study a new design to operate at a new voltage some time must be consumed in investigating possible insulators to fit this new line. Although the authors state that these natural pollution tests will give results in a short space of time, a speaker has shown that the longer times bring the more dramatic results and very frequently change the shading of choice between one insulator and another. Therefore, as a line designer, I should like to ask the authors when they think that they will be able to offer an accelerated industrial pollution test in a similar fashion to the work which they are now starting on marine pollution. This may well not take the form of previous attempts to tackle this problem, where there has been an endeavour to devise laboratory pollution. The only pollution which works, seen through the eyes of an engineer, is that which exists around us. If we hang an insulator in a natural atmosphere it will become polluted at a given rate. If we hang it in a chamber and draw the atmosphere past it at a considerably increased rate, will not the rate of deposition of pollution be increased?

I am very disappointed that, possibly through lack of facilities, the authors have been unable to be as definite about tension sets on overhead lines as they have about suspension sets. Lacking guidance from research, the design engineer is greatly tempted to keep cutting down on the tension sets, because, with the increasing use of multiple conductor lines, the ratio of tension sets in service is rising until on certain lines their use in the field matches that of suspension sets. In the past the tension set could be neglected on the ground of numbers, but it is now of equal importance.

It is all very well to say that we have evidence that tension sets are satisfactory because we have very little trouble with them. But why do we have very little trouble with them, and how much further can we go in cutting them? Are the authors satisfied with the present arbitrary ratio of the reduced leakage distance of tension sets as against the more positive knowledge of suspension sets?

The authors prove that the cap-and-pin string is superior to the rod type, and with that we all agree; but the cap-and-pin string introduces a further hazard which the rod type does not possess, namely that it has more joints. While the paper deals with the deposition of pollution on the insulating surface, there is the growing problem of pollution causing trouble in the joints between insulators and thus giving rise to radio and television interference. It is extremely difficult to measure this under any conditions, but it is an increasing hazard and plays a very great part when we come to decide the siting of lines in this very densely populated country.

Mr. M. C. Blythe: We have been carrying out a field survey on the reliability of, and the troubles experienced with, insulators on transmission lines, and have found the surprising result that most of the troubles reported to us refer not to the insulator itself, the porcelain or glass, but to the metal parts. We have found some extraordinary cases of troubles due to corrosion in the metal fittings attached to the insulators. There is a particularly interesting case which relates to an oversea line. In a pin insulator the corrosion has taken place under the insulator where the pin enters the cement, and it is so severe that these insulators have been falling off the line (see Fig. C). The

Fig. C

extraordinary thing is, however, that it is only on the centre phase of this line that it has been happening. The line is near the sea, and apparently salt pollution has caused the trouble, but it is evidently related to some electrical phemomenon.

Mr. J. R. Smith: I have three short questions. The first has been dealt with fairly well by previous speakers and concerns the position of tension insulator sets. At present, on the 132 kV Grid system approximately 35% of the strings are tension type, whereas at 275 kV, where duplicate tension strings are used, the proportion is about 50%. This implies that, if we could have some information on the limits to which we could reduce the length of tension strings, we might be able to effect an appreciable saving on line construction costs.

Secondly, the authors comment on the corrosion of the semi-conducting glaze which takes place near the caps or pins. Could

this be alleviated by grease or paint at the junction between the glaze and the metal parts? This would be particularly useful where the glaze is carried over only a part of the sheds to prevent radio interference.

Thirdly, might it be possible to improve the stress grading along an insulator string by using an asymmetrical string? In other words, this would mean either putting units with conducting glaze or high-capacitance units at the live end of the string to improve the electric field configuration.

Mr. J. W. S. Mather: B.S. 137 lists tests and mentions clean insulators to pass the standard test. These insulators are then installed in polluted areas without any further tests. In the Thames Estuary area, the pollution is that of cement dust. A recent estimate gives* 25 000 tons of dust emitted per annum. With the prevailing winds this is normally sent down the Thames Estuary; but when the winds veer to the north-east, as they can at this time of the year, the dust is deposited round the area where our transmission lines are situated and the insulators can become thickly contaminated, especially the varieties with the large anti-fog shields which are difficult to clean either by rain or by the linesmen, because of the broad skirting on the insulator. The cement dust which normally lies on the insulator is aggravated in November, December and January by thick fogs, which is when flashovers occur in this area. Do the authors think that the Clean Air Act will tend in future to diminish pollution in areas where it now exists?

Mr. C. J. O. Garrard: Have the authors seen the French rod-type insulator with a single helical shed down its whole length? It is stated to have good self-cleaning properties.

I support Dr. Last on the subject of conducting glaze. We have had some success in using it on surge-diverter porcelains to distribute the voltage equally over a stack of units. The joints between the caps and the glaze gave trouble that was overcome by silver-plating the ends of the insulators. I think that continued work directed to making conducting glaze cheaper and more uniform, and to dealing with the problem of joints, would be well worth while.

Messrs. J. J. Taylor and A. D. Lantz (*United States: communicated*): In Section 3.2 the authors discuss several types of surface treatment, and we are particulary interested in their comments on silicone compounds. In the United States, silicone compounds are applied as heavy undiluted coatings 1/32–1/16 in thick. On controlled tests such coatings have been more durable and satisfactory than an equivalent thickness of hydrocarbon greases, primarily because these latter coatings failed rather early by decomposition and the formation of carbonized paths. This may be related to the glaze damage exhibited in Fig. 5 of the paper, which has not been reported beneath silicone-type layers. In general, United States results indicate that the extra cost of silicone compounds is justified on the basis of the additional life expected between applications. In addition, the superior temperature/viscosity characteristics of silicones make it unnecessary to compromise 'drop' points for easy application and cleaning.

In Section 3.3, dealing with the control of voltage distribution, special mention is made of insulators treated to provide control of the voltage on the whole unit or section rather than over all parts of the exposed surfaces. This is of interest, and, recalling Dr. Forrest's earlier work with voltage-distribution control using external resistors, we would be interested in the authors' comments on the relative efficiency of a voltage control when done on a per-unit basis as compared with a control means associated intimately with the leakage surface.

The chemical cleaning discussed in Section 3.5.2 is reported to have affected the puncture strength of suspension insulators. We would be interested in learning whether these were glass or porcelain and whether the puncture was external to the metal parts or within the head of the dielectric. If the puncture were external, might this loss in puncture strength be caused by surface etching by the cleaning solution? It is possible that localized corona streamers in the surrounding oil could produce artificially low results on clean insulators. When polluted insulators were immersed directly in oil of high electric strength, it is possible that some of the conducting portions of the deposit could provide slight resistance grading throughout the oil, thus preventing high-temperature corona formation which tends to produce an artificially low breakdown on the disc portion.

The results of d.c. investigations described in Section 5 are particularly welcome and contribute useful knowledge toward a growing fund of information on d.c. effects. With regard to the corrosion effects described in Section 5.3, similar effects were observed on lower-voltage tests in our experiments. It was observed that the positive electrode tended to build up corrosion products. With positive pins, these deposits produced radial cracks in the dielectric material. With negative pins (positive caps) a scaly corrosion product at the edge of the cap developed sufficient pressure to crack the whole disc (circumferentially) away from the rest of the insulator.

[The authors' reply to the above discussion will be found on page 195.]

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, AT BIRMINGHAM, 9TH NOVEMBER, 1959

Dr. C. H. W. Clark: The performance of insulators when dirty and damp is variable, and the authors refer to erratic behaviour. One of the merits of their method of counting leakage current surges is that a large figure is obtained for each insulator, i.e. the number of surges recorded is several thousand. This represents the summated performance over a comparatively long time. The authors quite rightly point out that the basic question is whether flashover occurs, but actual flashover is comparatively rare and the number is therefore more seriously affected by variability than the number of leakage-current surges. Attempts to obtain a larger number of flashovers in a reasonable time by raising the test voltage are open to objection, and the counting of current surges remains the best method of obtaining figures to which statistical methods might be applied.

If one insulator counts 1 000 surges and another 1 100, is the difference significant? Perhaps not, but probably 4 000 on another insulator would be significantly different. The statistician might answer such questions by comparing the measured differences with the random variability shown by a number of identical insulators over a long period.

Have the authors used statistics in order to decide what is a significant difference? Since the weather shows great variability from month to month and year to year, I suggest that simultaneous testing would give rise to a lower variability and hence a greater significance for a given difference than tests of the same duration made at different times.

The variability of natural testing leads to the consideration of artificial tests in which 'weather' conditions can be repeated whenever necessary. The authors give details of artificial salt testing, which is comparatively simple. In service salt settles quite quickly on the insulator and the first time it rains most of it is washed off. Industrial pollution settles slowly on an insulator but is only partly washed off by rain. The final state of the insulator is thus the result of repeated cycles of dirtying

* A technically more correct rate of cement-dust emission is about 2 000 tons/month distributed as a fraction of one-tenth part over an area of 8 square miles.

and washing. If an attempt is made to develop an artificial industrial test it should include both deposition and washing finally followed by the damp conditions in which flashover may occur. Reference 25 in the paper is to French work which includes these cycles.

Have the authors been able to make a comparison between service performance of, say, hundreds or thousands of insulators on a line and the prediction from their own tests? This is the final criterion of whether their test method is really good.

With regard to cleaning by immersion in hot caustic soda, the authors point out that the cost of cleaning should include an assessment of the benefits of replacing the old insulators by newer and better ones. In addition, Portland cement, with which most insulators are assembled, may not take to immersion in caustic soda, and when it is put back into service, chemical reactions may be set up within the cement and lead to slow deterioration.

Mr. W. A. McNeill: For 15 or 20 years at least, engineers have been endeavouring to find a satisfactory criterion for the design and testing of insulators for use in polluted atmospheres. There have been attempts to reproduce atmospheric pollution under laboratory conditions, and some countries have introduced artificial tests into their national standards.

The problem, however, is one of great complexity and the performance will vary greatly depending on the incidence of cleaning rain, the likelihood of long dry periods, when pollution can settle followed by fog and condensation, and whether industrial pollution or sea-coast salt deposits are involved. Furthermore, the insulator designer has to take into account a condition which is not covered by the paper, namely, semi-desert conditions, where very high temperatures are also involved, coupled with surface pollution and night condensation.

In the circumstances it is not surprising that standard laboratory pollution tests have not found favour, and instead, in this country, we have adopted certain conventions for the design of weather sheds and for the lengths of leakage paths. Field tests of the type carried out by the authors are therefore of immense value in checking whether these conventions have been justified.

The anti-fog shed constructions called for in Great Britain are heavier and more difficult to manufacture than the plain sheds generally used in other countries. It is, therefore, disappointing to find that the paper does not analyse the results in more detail in relation to these factors.

I have tried to correlate surges per month against leakage path lengths, but it is difficult to find a clear relationship. I should like to have the authors' views on whether a more detailed study of shed design, protected leakage path, stress control, corona inception level, etc., of the insulators tested, would throw additional light on the performance and on the reasons for some of the rather anomalous results.

There are also some startling discrepancies between recorded surges and time to flashover, and I wonder whether 25 mA surges are truly indicative of the trend towards failure. I note that some investigators in America have used 50 mA as a criterion. This might be a better value to choose.

Finally, it is of interest that glass insulators with higher capacitances are undergoing test. As this has been achieved at the expense of thickness in the head, is there not a danger of puncture? There is no power-frequency routine voltage test called for in B.S. 137 for glass, although there is for porcelain. Although it is stated that the glass discs will withstand the impulse voltage tests, the latter is only a type test. Are the authors satisfied that the risk involved is outweighed by the improvement in voltage distribution achieved?

Mr. J. H. Hodge: I am interested in the influence of the cooling towers upon the testing station. Are the cooling towers fitted with spray arresters, which might restrict testing, and what would be the approximate position of the cooling towers in relation to the testing station?

Would it be practicable and desirable for silicones to be incorporated in the glazing of porcelain insulators during their manufacture?

Mr. E. V. Hardaker: In the early days of the 132 kV Grid system, flashovers due to pollution occurred in the Midlands Division at substations near those generating stations where there were cooling towers and where pulverized fuel was used. The fitting of spray eliminators to cooling towers, and the increased efficiency of electrostatic precipitators, have considerably improved the situation, and no serious trouble due to pollution is now experienced. Where frequent live washing was carried out in the early days, it is now necessary only at very long intervals.

There are many different types of insulator discs in use, and provided that there is no serious difference in cost, it might be worth while considering standardizing on an anti-fog type. The cost may not be any greater, since such a type may permit the use of an insulator string of less overall length.

It is a little surprising that the stabilized insulator is not yet regarded as sufficiently satisfactory to be specified universally. There are 12 such insulators (all on cable sealing ends) in the Midlands Division, and they were installed between 1947 and 1948. These insulators are still in commission and have given satisfactory service. Apart from a slight initial corrosion of the glaze, which occurred shortly after being commissioned, there has been no further deterioration.

Mr. H. F. Jones: Much valuable information may be gained from artificial tests. It is extremely difficult to interpret the results of pollution tests under site conditions owing to the many uncontrolled variables. When I was concerned several years ago with tests on porcelains having semiconductor glaze the actual effects which seem to precipitate flashover were very localized even on the porcelain surface itself. I doubt whether uniform atmospheric conditions exist over the space required for quite a small quantity of porcelains, even in a place as dirty as Croydon. How then can one make reliable comparison between two stacks which are close together and switched on on the same day, even if left there for several years? Can one be certain that arbitrary currents of 25 and 150 mA have any basic meaning when one attempts to assess various designs of stacks? I should have thought that eventually one has to come round to artificial testing—not too complex a test, but one which is controlled, for example, in the manner of those described in Reference 20 of the paper. These use a saline solution, with compressed air to give a fine mist and cement dust applied in layers. This cannot hope to represent typical working conditions, but it seems to be a more reliable way of comparing two types of design of porcelain, because major physical changes in design may produce negligible effects on the actual number of surges, and conversely minor changes can produce quite large changes in the number of surges. May not such results be the effect of localized surface conditions?

Another thing which seems very valuable in this work is the application of high-speed photography to observe the behaviour of sparking over the dried-out and wet portions of the insulator surface. This could provide a better understanding of the local contamination.

With regard to the effect of semiconductor glaze, I agree that this has quite a wide application provided that certain precautions are observed. I think the initial poor performance was, first, due to the fact that it was used on cap-and-pin insulators, where the area of contact was necessarily small and the local current density was therefore high, which we now know from

experience to be a bad condition, and, secondly, attention was not paid to increasing the conductivity of that area to give a better contact condition. I agree with the authors that these electrolytic actions are happening, but I feel that it will be many years before they have a serious effect on the voltage distribution in relatively large porcelains such as post insulators, bushings or surge-diverter porcelains.

I believe some years ago the Germans or French actually did some tests on coating insulators with a solid or plastic material in order to improve pollution resistance. Have the authors any later information on this?

Mr. T. R. Bird: I think that it would be almost impossible to incorporate silicones in the glaze on insulators owing to the very high temperature at which they are fired. Various silicone compounds can be baked on to the finished insulators, and these give it a durable finish. On the question of surface treatment, an American investigator has reported very encouraging results with the use of silicone waxes applied by hand cloths, but, so far, his results have covered only about two years, and a longer period will be required before any definite conclusion can be drawn.

I think that the whole key to the problem of pollution lies in the figures giving the rate at which solids are deposited from the atmosphere at Croydon. 78 tons per square mile per month is a terrifying figure, and it is surprising that insulators are successful under these conditions. In discussing this problem with engineers up and down the country, it is claimed that conditions are far worse than this in places. Have the authors any comparative figures for pollution at other sites? It is difficult to visualize what 78 tons per square-mile means; it would be clearer if the figure was given in ounces per square-yard, and this works out at $0 \cdot 9\,\mathrm{oz/yd^2}$, which is easier to relate to the surface of an insulator.

I agree with the authors that flashover must be the final criterion of performance. I have attempted to analyse the figures for surges recorded in Table 1, which gives the results of suspension insulators at 132 kV, but if we are to accept that these surge counts are a reliable guide to performance we must admit that very small changes in insulator design produce very large changes in performance. Insulators Nos. 1 and 2 in Fig. 2 are very similar, and yet one has recorded many more surges than the other (see Table 1). The 10-unit set of No. 1 has recorded 327 surges in 53 months, while the 10-unit set of No. 2 has recorded 2 314 surges in 58 months. Insulators Nos. 3 and 4 are also similar, but one of the 10-unit sets has recorded 4 022 and the other only 1 344 surges in the same period.

Have any tests been done in which a number of identical strings have been set up and tested for exactly the same period under the same conditions? If such a test were done would the surge figures be comparable?

Mr. S. M. Gonek: It is sometimes necessary, particularly on high-voltage circuit-breakers, to mount the insulators at angles other than vertical, and insulators with their axis at 45° or even horizontal are used. Depending on a manufacturer's ideas, the sheds may be of the anti-fog type or, at the other end of the scale, plain and at right angles to the axis. It is generally recognized that the service performance of such insulators is superior to the vertically mounted ones, but the published data on this subject are inadequate to design them with the degree of certainty applicable in the case of the latter. Have the authors carried out comparative tests on inclined and horizontal insulators, and, if so, with what results?

The authors quote typical rates of deposition of solids, which, one can assume, take place in the absence of strong electric fields.

Have the tests yielded any information on the actual deposition rates on energized insulators? Was the improvement obtained on insulators with conductive glaze also due, to an appreciable extent, to lower rates of contamination caused by weaker electric fields?

In Fig. 6 and 9 an appreciable increase in leakage current is shown to occur when the relative humidity approaches, and exceeds, 80%. Can this be taken to represent an onset value for clean insulators, and could the authors comment on variations in this value in relation to the condition of the insulators?

Mr. J. S. Cliff: Despite all the work which the authors have carried out, B.S.I. committees dealing with insulation still cannot put forward any reasonable proposals for testing insulators to assess their suitability for installations subject to heavy atmospheric pollution. It is true that creepage length has been specified, but reliance is still placed upon the wet flashover tests which are carried out on clean insulators. The authors' tests have shown that these can be of very little value.

On the Continent a considerable amount of work has been done in an attempt to evolve an artificial pollution test which can give a quick assessment of the performance of a given type of insulator. These tests need to be correlated with service experience in polluted atmospheres, and Croydon appears to be a suitable place for doing this, but so far little has been done on the problem. The authors have made a start with their salt-spray test, and it is to be hoped that this will be extended as quickly as possible to other artificial tests so that a satisfactory test, which can be used in specifications, is evolved as soon as possible.

It is surprising that bushings have not also been tested at Croydon. In my experience with 132 kV substations in polluted areas the condenser-type bushings have given a very much better performance than post insulators or insulator strings. This is probably due to the better voltage distribution obtained across the porcelain, but it would have been interesting to have had some check upon this performance at Croydon.

The authors show that the difficulties increase very considerably with voltage, and the 380 kV system is likely to be very susceptible to pollution. As the voltage increases and the power transmitted over a single line becomes larger, it is increasingly important to avoid flashovers, otherwise the stability of the whole national system may be jeopardized. As serious consideration is now being given to the use of a voltage of approximately 525 kV for major interconnectors in this country it seems essential that work on pollution problems at this voltage should be undertaken immediately if a satisfactory answer is to be achieved before the system is required for operation.

Mr. H. Davies (*communicated*): With reference to Section 3.4, cast epoxy-resin insulators have, I understand, been adopted for certain high-voltage outdoor applications on the Continent. Outdoor installations have also been on test in the United States for some years. While there is a certain amount of conflicting evidence as to the suitability of these resins outdoors, particularly in polluted atmospheres, they appear to have been successful in many cases. It is interesting that the epoxy-resin insulator tested by the authors had not shown signs of erosion or tracking when it flashed over. So far as I am aware there has been no experience of epoxy-glass or polyester-glass laminates at high voltage outdoors.

An investigation of the problem involves many different factors. With respect to the resins alone there are many different types of resin-hardener system and a variety of fillers to be considered amongst other factors. When glass fibres are introduced the problem is further complicated, as the authors point out, by factors such as the surface finish of the glass, the resin-glass bond, the presence of moisture on the glass, air occlusion, etc. These particular difficulties could probably be

minimized by the use of a thick section of casting resin around the glass reinforcement provided that due care is taken in the mechanical construction. There is also the possibility of coating the resin with an impervious inorganic coating. An investigation into these matters is being undertaken, and it is hoped to obtain useful information in due course.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Dr. J. S. Forrest, and **Messrs. P. J. Lambeth** and **D. F. Oakeshott** (*in reply*): Such a large body of literature has been devoted to insulator pollution that we felt bound to limit our references to more recent published work, but we would by no means relegate Mr. Ryle's very useful paper to 'pre-history'.

The number of pollution faults varies widely from year to year, and even a 5-year period is insufficient to give a stable mean. For example, the mean fault rates per 100 route-miles per year at 132 kV for the period 1954–59 were 0·80 for industrial pollution and 0·22 for salt pollution. The annual values vary over a range of 6 : 1.

Little trouble is caused in practice by the uneven surface of hand-applied grease, or by the adhesion of wind-blown straw or leaves, as the heavy grades of grease used are not very sticky at normal temperatures. The method of applying grease described by Mr. Todd gives a better finish, and he and his colleagues are to be congratulated on the way in which they have developed mechanical methods of greasing and cleaning insulators.

The use of semiconducting bodies mentioned by Mr. Ryle has been considered, but a major difficulty is finding a suitable material which has the right electrical and thermal conductivities as well as good mechanical strength.

Messrs. Ryle, Jackson and Smith ask for information on tension sets, and Mr. Gonek asks for guidance on inclined insulators. Tests at Croydon have shown (Reference 2 of the paper) that tension insulators behave favourably in industrial areas, as Dr. Last states. We are studying the performance of tension insulators at Brighton, since we expect their performance in coastal conditions will not be so good. The behaviour of inclined insulators might well be investigated in the future by means of artificial pollution, but we have no specific information on the subject at present.

We agree with M. Leroy on the three essential types of test, but would put them in reverse order in respect of time. Ideally, one should select an insulator by an artificial test, confirm its performance by a natural pollution test, and the subsequent service experience constitutes the result of the third test. We are anxious for the Croydon test results to be verified in the field, and, in fact, the first 380 kV line in this country will be used to test several different designs of insulator. We assure M. Leroy that we would not use the artificial salt spray test alone in comparing insulators for any kind of pollution.

We sympathize with Mr. Broughall in the insulator problems of the railways with both heavy pollution and steam. A steam cleaner has been successfully used to remove dirty grease from insulators, but we have not used it on plain porcelain insulators.

The correlation of data from other test sites, such as Mr. Johnston's, and the assessment of the degree of pollution at sites for substations are of great interest to us. We consider that meteorological data, rates of pollution deposit and the amounts of sulphur compounds in the air, while of interest in themselves, are too indirect to give the comparison we need. We have energized small insulators at various sites at 230 volts, and the recorded leakage current should give a good idea of the pollution severity. We would hesitate to compare sites on the basis of results for insulators energized at different voltages.

We have carried out investigations with a number of surge counters operating at different currents and concluded that one counter operating in the range 20–50 mA is adequate, although it is important for comparison between insulators that all the counters operate at the same value.

The difficult question of interpreting any surge count was raised by Dr. Clark and Messrs. Jones, Bird and McNeill. We have avoided being too definite in our statements in the paper on the comparative performances of two insulators based only on the surge counts, unless these differ by several times. We hope that an experiment now in progress will enable us to give a more precise answer to the question in the future.

The difference in performance between insulators Nos. 2, 3 and 4 and insulator No. 1 in Fig. 2 is probably significant. The reason for the difference is possibly that insulator No. 1 has a short outer skirt permitting air circulation and rain washing between it and the next skirt and a greater leakage path than insulator No. 2, so that there is less risk of a spark between the two skirts short-circuiting a substantial part of the leakage path.

We endorse Mr. Cherry's viewpoint that more space is required in order to test a larger number of insulators, preferably several of each type, for the highest system voltages.

Mr. Simpson's experience with silicone compounds is similar to ours, and we are pleased to hear of the success of Messrs. Taylor and Lantz with a rather thick layer of this compound. Although the glaze damage with hydrocarbon greases may be due to carbonization, we would not rule out the possibility of similar damage occurring with silicones.

The plastic cross-arm and insulator shown in Figs. A and B are an example of the radical alteration in design to which we may look forward when synthetic materials are improved and the spark erosion and tracking problems are mastered.

In his comparison of the test results for insulators Nos. 1 and 5 in Fig. 2, Dr. Clark has ignored the fact that the porcelain insulator flashed over and the glass one did not. However, we agree that there may be sufficient differences in the designs to swamp any effect due to differences in the materials.

Our statement that after less than a year the rate of surge counting becomes independent of the time that the insulators have been energized has been verified from the study of a large number of insulator histories and is not contradicted by Fig. 8. The differing counts for each year are due to the different degrees of severity of the weather.

We are wholly in agreement with Messrs. Jackson, Jones and Cliff on the need for a suitable artificial pollution test, and we are aiming at such a test or series of tests. They will complement, rather than supersede, natural pollution testing.

The insulator pin corrosion shown in Fig. C may be the result of leakage currents and flux left on the pins. The relative immunity of the outer insulators on the unearthed wood-pole line could be ascribed to the additional insulation of the wood of the cross-arm.

The life of a near-cylindrical semiconducting-glaze insulator will be many years, as Messrs. Jones and Hardaker mention. Unfortunately, grease or paint coatings of the glaze-cement junction have been found to give only temporary protection of the glaze. Mr. Smith's other suggestion that insulator performance would be improved by grading capacitance to give a uniform voltage distribution is feasible, but we consider that the resulting slight improvement in performance would not justify the complication.

We have not yet tested the French helical insulator which Mr. Garrard mentions.

In answer to Mr. Hodge's query, the cooling towers at Croydon are not fitted with eliminators. They lie 100–400 yd from the test site in an arc lying roughly between south-west and north-west.

Mr. Jones draws our attention to Continental tests on plastic coatings. Our own experience recently with p.t.f.e. and p.t.f.c.e. coatings on porcelain has been disappointing.

In answer to Messrs. Taylor and Lantz, we consider that controlling voltage distribution by units is not so effective as control over the whole insulator surface, but it gives a greatly improved performance over an unstabilized insulator when the number of units is ten or more.

The porcelain insulators cleaned with caustic-soda solution punctured at the edge of the caps. Of the reasons for the reduced puncture strength put forward by Messrs. Taylor and Lantz, etching of the glaze is more likely than a low resistance on the dirty insulators, since the pollution deposit was a thin non-conducting bituminous layer.

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APPLICATIONS OF ELECTRICITY IN AIRCRAFT

A Review of Progress.

By V. A. HIGGS, B.Sc., Associate Member.

(1) INTRODUCTION

Since this is the first review of its kind, it will be useful to devote some space to a historical survey. Fortunately aeronautics is a comparatively young science; many of the pioneers are still living, and some hold responsible positions in the industry which has grown out of their enthusiasm and courage. Each stage in the development of aircraft has brought new problems for the accessory manufacturer, so that it is advisable to review, to a limited degree, the development of the aeroplane itself.

Ever since he began to think for himself, man has envied the birds their ability to fly; but many attempts to imitate them ended in disaster before it was realized that the bird's power/weight ratio is far greater than can be achieved in any device operated by man-power alone. It was not until the petrol engine was suitably developed that the Wright brothers were able to make the first successful flight. But the petrol engine was very unreliable until the electrical engineer developed a satisfactory and reliable method of producing an accurately timed spark at the appropriate part of the compression stroke. The device used to achieve this was the magneto, so that in some measure the electrical engineer can claim to have contributed to the success of the Wright brothers. The first successful magnetos were made by Bosch, and until 1914 practically all aircraft engines were fitted with these. This state of affairs naturally could not continue during the war, and the aircraft electrical-accessories industry was started in Great Britain, first by making copies of German magnetos and very soon after by developing its own designs.

(1.1) Development before 1939

A number of Institution papers have described the early development of electrical accessories for aircraft, two notable examples being those by Hockmeyer[1] and Follett.[2]

The military significance of the aeroplane was not realized at the beginning of the 1914–18 War, although in 1912 the British Government called for official trials of a military aircraft which was to have an endurance of 3 hours, including 1 hour at 4 500 ft, carrying a load of 350 lb at 55 m.p.h. Once aircraft came into use it was found necessary to maintain communication between them and their bases, and the first application of electrical power was to operate wireless. During this period development was confined mainly to magnetos and windmill-driven generators.

Between the two wars the importance of the aeroplane as a means of transport was realized only by a few men of vision, and flying was generally considered to be a rather dangerous and expensive sport. In fact, all the major developments in this period were the direct result of some competitive event, usually in the form of an air race over a route which was later to be used for air mails or air transport. An excellent example of such an event was the MacRobertson International Air Races from England to Australia, which began on Saturday the 24th October, 1934; according to the official programme:

> The International Air Races from England to Australia owe their inception to the generosity of Sir MacPherson Robertson, a leading citizen of Melbourne who, to encourage aviation and to mark the centenary of the State of Victoria and the City of Melbourne, has given £15 000 and a Gold Cup worth not less than £500, to be awarded as prizes in air races from England to Melbourne. . . . Competitors in either or both races must complete the course within sixteen calender days; all pilots who fulfil this requirement will receive a gold medallion.
>
> Two races will be run concurrently, a Speed Race and a Handicap Race. The starting point is Mildenhall Aerodrome, Suffolk, a new Royal Air Force Station placed by the Air Ministry at the disposal of the Royal Aero Club.

The first aircraft to reach Melbourne was the De Havilland Comet Racer, which won the speed race; the second, which won the handicap race, was the American Douglas DC2 entered and flown by the Royal Dutch Airlines (K.L.M.). This was a 14-seat passenger aircraft of approximately 18 000 lb weight and was the forerunner of the very successful DC3 and DC4 designs.

During the period between the wars the electrical installation in aircraft followed a pattern similar to that used in automobiles, and was in the main confined to the provision of power for radio, lighting and heating. However, in 1938 the De Havilland Company introduced the Albatross, a new 23-seat passenger aircraft of approximately 30 000 lb weight for Imperial Airways.[3] This aircraft was a direct descendant of the Comet Racer, and was the first British aircraft to make extensive use of electricity as an auxiliary power supply: electrical power was used to operate the undercarriage, the flaps and other devices normally actuated hydraulically. The 1939–45 War prevented the full exploitation of this aircraft, but its further development led to the famous Mosquito.

(1.2) Development between 1939 and 1946

The 1939–45 War was a period of such intense and rapid development of aircraft and the application of electricity in them that it is impossible to record the progress in a true chronological order. Like the war itself, the development began slowly, but this time the military significance of the aeroplane was realized from the outset. The immediate demand was for large numbers, and this meant large-scale production of as few standard designs as possible, particularly in regard to accessories. The standard set for the electrical power supply in aircraft at this time was the nominal 24-volt single-wire earth-return d.c. system.

During this period large increases in electrical power requirements were caused by an increasing demand for radio, the introduction of airborne radar, the addition of electrically operated flying instruments, and the replacement of hydraulic auxiliary power by electrical power. Each of these factors had a profound effect on the development of aircraft electrical power systems and the associated accessory equipment. It is interesting to note that American experience during this period was similar to the British despite the fact that the aircraft problems were somewhat different.[4]

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(1.2.1) **Radio and Radar Equipment.**

The increasing use of radio and the greater operating range demanded as aircraft flew faster and higher meant that the voltage regulation of the power supply became increasingly critical.[5] Of much greater significance, however, was the influence of radar equipment, which requires very high voltages for the magnetron transmitter and the cathode-ray-tube indicator. To obtain these high voltages it was necessary to provide a.c. supplies from which they could be readily derived by using suitable transformers, and the first specification for an aircraft alternator for radar power supplies stated that the machine should be without brushes, of high frequency (any value above 1 kc/s) and of any voltage. This specification was met by using inductor-type alternators, and engine-driven units with outputs up to 18 kVA were developed and used during this period.

When operated over a range of speed the inductor-type alternator does not have a very good power/weight ratio; and since every radar equipment had to be provided with an accurate time-base, it was evident that weight could be saved, both in the radar equipment and the alternators, if the frequency could be closely controlled. By driving the inductor alternator with a d.c. motor and controlling the fields of both the motor and the alternator it was possible to provide a.c. power at constant voltage and frequency from a d.c.-mains power system. In military aircraft with large radar installations the saving of weight in the radar equipments and the alternator more than compensated for the extra weight introduced by the d.c. motor, its control and the increased size of the main generators. The motor-generator sets so introduced were given the generic title of 'inverters', together with other motor-generator sets introduced for other purposes.

In the later years of the war the satisfactory operation of the radar equipment in the aircraft was essential in order to permit the machine to complete its military mission, so that the power requirements of this equipment became the most important factor in the design of the electrical power system.

(1.2.2) **Electrical Flying Instruments.**

Early gyroscopic flying instruments were air-driven, but these types were not satisfactory for operation at high altitudes and for large changes in aircraft speeds. They were replaced by electrically operated units, first with d.c. power and later with a.c. power.[6, 7] The high-speed a.c. induction motor is the obvious choice for a gyroscope, particularly if built with the rotor outside the stator. Units were developed to operate from a 400 c/s 3-phase 115-volt supply, and inverters were used to provide this supply from the normal aircraft d.c. mains. Once this supply became available in aircraft, other uses for it were soon found, notably in radar equipments where it is used for small motors driving fans for cooling. As the units comprising a radar installation are reduced in size, it becomes necessary to provide internal and external cooling to dissipate the heat generated by the valves, etc.

(1.2.3) **Electric and Hydraulic Actuation.**

Reference has already been made to the 'all-electric' Albatross aircraft, but at the beginning of the war the established auxiliary power supply was hydraulic. It was soon found, however, that electrical power lines were far less vulnerable to enemy action than hydraulic pipe lines, and thus increasing use was made of electrical power, particularly in American aircraft. The electrical loads provided by such applications are usually of short duration but large capacity and in some cases could cause serious disturbances to the main power system. As aircraft became larger and faster it became necessary to assist the pilot to operate the control surfaces. In the period relative to this Section of the review, however, it was always possible to revert to manual flying control.

The operation of control surfaces, etc., requires large reversible forces, usually over comparatively short distances. These forces can be provided by electric motors with suitable mechanisms; such devices are known as actuators and a complete range capable of producing thrusts up to 10 000 lb or more are available. For large forces which must be quickly and immediately reversed—as is usually the case in flying controls—the hydraulic ram is lighter and more suitable. In these cases a convenient marriage between hydraulic and electric operation provides the best solution by distributing the power to the appropriate parts of the aircraft electrically and providing a motor-driven pump and hydraulic ram unit at the control surface or device to be moved.

The most serious effect of the growth of this type of electrical load was that it caused the capacity of the electrical power system to increase more rapidly than the ability to protect the system against possible fault currents.[8]

(2) PROGRESS SINCE 1946

With the increasing demand for electrical power it was obvious that the nominal 24-volt d.c. system would have to be superseded by one at a higher voltage; proposals for such systems were first made in Great Britain in 1936 and started the controversy, which has been going on ever since, between a.c. and d.c. power systems. The advantages of alternating current cannot easily be ignored, and during the war the Short Shetland flying boat was equipped with an a.c. power system derived from alternators driven by separate auxiliary engines.[9] A system in which the electrical power supply is independent of the aircraft main engines is ideal electrically, but, unfortunately, small auxiliary engines are heavy and uneconomic when designed to operate at very high altitudes; furthermore, the advent of the gas turbine increased the difficulties of obtaining a satisfactory small auxiliary engine. Although small gas turbines can be built with fairly good power/weight ratios, their fuel consumption is still high and it is more economic in weight to burn this fuel in the main engines. If the main aircraft engine is retained as the drive for the alternators, it is necessary either to accept a system in which the frequency varies or to introduce an infinitely variable-ratio gear (constant-speed unit) between the engine and the generator. It is to be assumed that the electrical engineer will never persuade the engine designer to develop an aircraft engine that will operate efficiently at a fixed speed, although it is the author's opinion that this might be possible, particularly in a twin-spool turbine. Constant-speed gears are devices which one would not fit to aircraft if there were satisfactory alternatives, and there has been considerable thought and effort devoted to a variety of both a.c. and d.c. power systems.

This uncertainty as to the correct power supply for aircraft also existed in the United States, for in 1951 a report by the American Advisory Staff for Aircraft Electrical Systems stated that 36 varieties of electric power requirements for accessories then existed. The report[10] recommended that only the three following systems should be recognized as standard for aircraft use:

- 320–1 000 c/s, 115–200 volts, 3-phase, variable-frequency.
- 400 ± 20 c/s, 115–200 volts, 3-phase, constant-frequency.
- 28 volts, direct current.

In Great Britain, however, it is intended to standardize on the latter two systems only, and if possible to eliminate the use of the 115-volt a.c. system.

The most important advance made since 1946, however, is the recognition of the power supply as an entity of its own requiring design considerations and a specification.[11] Originally,

the electrical power system was a collection of a number of items of equipment, usually bought from different sources and in many cases never operated together until installed in the aircraft. To-day the safety of an aircraft is usually dependent upon the integrity of its electrical power system, and now it must be designed and developed as a complete system, including tests on a ground rig prior to installation in the aircraft. Although for the purpose of this review it is convenient to consider the generating system separate from the distribution and utilization systems, it must be remembered that they are all interdependent. The correct choice of generator system can be determined only after consideration of all possible electrical loads.[12] For example, the choice of a medium-voltage d.c. power system for the Saunders-Roe Princess flying boats was determined primarily by the nature of the main electrical loads in the aircraft.

(2.1) Electrical Power Systems

The nominal 24-volt d.c. system has been developed and applied to aircraft with generator outputs up to 400 amp per unit. There are two obvious limitations to the extended application of this type of power system, namely the heavy weight of cables and the difficulty associated with heavy-current commutators particularly when operated at high altitudes.[13, 14] The latter problem can sometimes be limited to the main engine-driven generator, since all high-altitude aircraft must provide pressurized compartments for the crew and the passengers.[15] In civil aircraft it is common practice to install most of the accessory equipment within the pressurized volume, but in military aircraft the pressurized volume must obviously be kept to a minimum and thus accessory equipment is not installed therein if it can be avoided. Thus in civil aircraft the commutator problem can be overcome by using a combination of engine-driven alternator and rectifier to obtain the required d.c. power, and this type of system was pioneered in Great Britain.[16]

The introduction of rectified a.c. systems made possible the extended use of medium-voltage (115-volt) d.c. systems, which in turn introduced added problems to the operation of switchgear and adequate protection against electrical faults.[17] In the course of developing control gear for use on these systems it was found that there was considerable room for improvement in the methods of control and protection used in low-voltage d.c. systems. A complete range of d.c. switchgear has now been developed, including circuit-breakers capable of rupturing fault currents of 10 kA at 70 000 ft for use on both 28- and 115-volt d.c. systems. To-day the only acceptable d.c. system voltage is 28 volts, and at this voltage the application of d.c. power is limited by cable weight. For low-altitude low-speed aircraft with comparatively small electrical power requirements, d.c. power systems with d.c. generators are the most suitable. For high-altitude aircraft, alternators and rectifiers should be used; once these are introduced the possibility of using the variable-frequency power for heating and other loads which are insensitive to frequency is available.[18] A rather special form of this type of power system was developed for the Bristol Brabazon aircraft,[19] using tap-change transformers to assist in the operation over a wide range of engine speeds. The Britannia and the Comet 4 are examples of modern aircraft using a.c./d.c. electrical power systems; the Comet[20, 21] is also the first aircraft to fly with d.c. power derived from silicon rectifiers. It should be noted that, where electrical de-icing is used, the loads can be very large indeed (up to 100 kVA), and the use of constant-frequency power for these loads is neither necessary nor economic.

Despite the success achieved with mixed a.c./d.c. systems, the constant-frequency fully-paralleled a.c. system has been the target before the aircraft electrical power-system engineer. In the United States considerable experience has already been obtained with a.c. systems using hydraulic constant-speed drives, and there is new British development which shows very great promise.

An alternative solution is to drive the alternator at constant speed by means of a turbine driven by air bled from the main engine. Such arrangements are usually lighter than a constant-speed gear, but the overall efficiency is lower, so that they are profitable only in fighter or other short-range types of aircraft.[22] Examples of air-turbine drives are available in both America and Britain. The efficiency can be improved if fuel is burnt in the air bled from the main engine, but there has so far been little experience with 'bleed and burn' systems. A description of these drives is not appropriate to this review. There are also a number of electrical solutions to the problem of obtaining constant frequency from a variable-speed machine, but so far none of these appears to have the features necessary to make them acceptable for aircraft use.

Constant-frequency power systems are now in use in British aircraft,[23] and although it may appear that in this development the British have lagged behind the Americans, this is true only in regard to the development of constant-speed gears. In aircraft such as the Hermes, Ambassador, Comet and Britannia the British accessory manufacturers have obtained hundreds of thousands of hours of operating experience with aircraft alternators and the associated control under conditions much more difficult than those which apply in constant-frequency systems.

(2.2) Engine Ignition and Starting

The first gas engine to use electric ignition was made in 1860 and used an induction coil. Marcus, of Vienna, took out the original patent for a low-voltage magneto in 1883, and the first really successful high-voltage magnetos were developed in Germany in 1900–02. The next major advances were of British origin, the polar-inductor design being introduced in 1918 and the rotating-magnet design in 1925. This latter type, which was first introduced for motor cars,[24] became the basis of the design of practically all future magnetos for aircraft engines.[25] Since that time most of the improvements have been achieved by the development of better magnetic materials and contact-breakers, etc.[8] In some cases an additional magneto, usually turned by hand, was fitted to assist in starting. By 1937 the 'hand starter magneto' was replaced by a high-voltage booster coil operated from the battery during the engine starting cycle.

As aircraft engines became larger and were built with greater numbers of cylinders the distributors became very bulky, especially where it was necessary to handle high voltages at high altitudes. To solve this problem the wheel of development turned full circle when low-voltage ignition was re-introduced. In this form a low-voltage generator is used and the 'sparks' are conducted at a low voltage to dual transformers mounted at or near to the plugs in the engine cylinders. With the development of the gas turbine for aircraft use this form of ignition came too late for extensive use on British engines, but it has been used successfully on American engines such as those installed in the Boeing Stratocruiser. During the long period of its use the aircraft magneto has been developed for operation up to 45 000 ft and in aircraft flying in excess of 400 m.p.h.

Early gas turbines were ignited by using booster coils, as mentioned above. Lighting a gas turbine is akin to lighting a Primus stove in a gale, particularly if it has to be done in flight, and thus an electric spark of considerable energy is required. The development of high-energy ignitors for aircraft engines began about 1946 and a 12-joule unit[26] was in production by 1948; the device consists of a circuit in which a capacitor is continually charged and suddenly discharged through a special

plug in the engine. Compared with a magneto, the high-energy ignitor is relatively simple, but nevertheless it has had, and is still receiving, development—mainly concerned in achieving greater energy for less volume and weight while still being able to exist in the conditions surrounding gas turbines when used in aircraft.

The idea of fitting a device which can be used only to start an aircraft engine and thereafter carried around as dead weight is not very attractive to aircraft designers. However, apart from the danger, the method of starting aircraft engines by swinging the propeller by hand soon became impractical and electric starter motors were introduced. Starter motors have been developed in various forms, and since these are used only on the ground, they can be and are the most highly rated electrical machines used. Because of this it is probably true to say that most of the advances in machine design leading to more output from less material originated in starter-motor designs. Many attempts have been made to use a starter-generator, thus avoiding the use of two separate machines. This is a practical arrangement only if the machine can be designed primarily as a generator but given sufficient capacity to start the engine when operating rather indifferently as a motor.

The starting requirements of the gas turbine are very different from those of the piston engine, since after initial light-up it is still necessary for the starter to assist the engine up to its minimum idling speed. When the time to start is of no consequence, an electric motor or a starter-generator is ideal. Unfortunately, in many applications—particularly fighter aircraft—a rapid engine start is required; for this purpose a small turbine device—the 'turbostarter'—has been developed and the largest turbine can now be started and brought up to speed in 10 sec or less. The turbostarter is essentially a mechanical device, and an account of its development is not appropriate to this review, but it is of interest to note that it was an electrical firm who pioneered the application and development of this form of engine starting. A complete review of all forms of aircraft engine starting systems has recently been given by Woodall.[27]

Efforts were made to use a starter-generator on the Vickers Valiant, but the disturbance to the commutator surface caused by the 'motoring' currents adversely affected the operation at high altitudes. One of the features of the new Hobson constant-speed unit is that it will accept power in the reverse direction, so that it is possible to use a starter-alternator. Provided that a.c. power is available, a brushless alternator can be run as a synchronous motor through the Hobson gear acting as an infinitely-variable-ratio gear, thus eliminating the need for separate starter motors.[28]

(2.3) The Electrical Installation

The complete electrical installation in a large modern aircraft has all the problems of distribution and utilization applicable to a power installation for a fair-sized community plus a number of additional and difficult problems peculiar to aircraft. This has not always been so, and it is only of recent years, when the integrity of the complete aircraft may depend on the electrical system, that the electrical engineer employed in the aircraft industry has received professional recognition. Originally the electrical team at an aircraft firm were regarded as a 'gang of wiremen', but it is largely due to their efforts that the installation of electrical power in aircraft has progressed at the rate that it has.

Wiring was undoubtedly one of the earliest problems, and the history of the development of special cables and wires for aircraft reads like the development of synthetic fibres. The first special aircraft cables were called the Proof type and were introduced in 1920, the insulation being a vulcanized rubber, protected with a paint-impregnated cotton braid. An additional layer of cotton braid coated with cellulose lacquer was introduced in 1932 and formed the Cel range of cables; these were replaced by the Vin range in 1940 and the Pren range in 1947. In the Vin series the lacquered braid was replaced by a continuous sheath of plasticized polyvinylchloride, and in the Pren series the vulcanized rubber was replaced by a glass braid followed by vulcanized polychloroprene. The introduction of nylon gave rise to the Nyvin cables in 1957 and the Nypren cables in 1959. Silicon rubber was first used in combination with glass braid in the Glasil range of cables introduced in 1950.

A similar story could be told of the development of a complete range of motors, switches, circuit-breakers, relays, contactors, inverters and many other items of equipment for use in aircraft. All this has arisen from the efforts and enthusiasm of 'the gang of wiremen', often maintained without much support either from the aircraft or the electrical industries. The Institution's Convention on Electrical Equipment of Aircraft (Vol. 103 A, Suppl. 1) deals adequately with this Section of the present review.

(3) FUTURE TRENDS

We are now standing at the frontier of space, and a new form of aviation has already been born which will bring with it new and more difficult problems for the electrical engineer.[29] But there still remain many development problems to be solved for the improvement of normal air travel. The immediate future generation of new aircraft will, in the main, be refined versions of existing civil types, and will operate at speeds less than 1 000 m.p.h. The development of electrical equipment required for these aircraft will consist primarily of improving the reliability of existing basic designs. An extensive range of d.c. and a.c. equipment is already available in this country, and this includes brushless designs of both d.c. and a.c. generators. The vast experience obtained with variable-frequency supplies in British aircraft should help rather than hinder the introduction of constant-frequency power systems. The development programme envisaged is one in which equipment is made more resistant to greater changes in environmental conditions, more robust and more easily maintained. It must be remembered that much of the equipment now available, both d.c. and a.c., was developed under the stimulus of war, when maximum aircraft performance for a short life (100 hours) was the all-important criterion. In civil aircraft a long reliable life (say 3 000 hours) is required, and tremendous advances have already been made in this direction without any major increase in equipment weight. The electrical power systems selected for these new aircraft will certainly use brushless generators and probably a.c. power at constant frequency. The essential property of air travel is speed, and there is no limit to the advantages to be obtained by increased speeds. There is a requirement for a civil aircraft operating at 1 500–2 000 m.p.h., and design proposals for such an aircraft have already been prepared. The development of a supersonic airliner and its equipment is of national importance and deserves the full and active support of the British Government.

At 2 000 m.p.h. there will be new and difficult problems for accessory manufacturers. Because of the difficulty in operating hydraulic systems at high temperatures, auxiliary power will have to be electrical, probably operating at 400 volts and 800 c/s. The operating temperature of some items of equipment will have to be increased to 300 or 400° C, and as operating speeds increase still further, temperature will be the main problem. It is already possible to convert heat to electricity directly with static equipment, but only at very low efficiency; further development of

this process with new materials may be the means of defeating the 'thermal thicket'. There is undoubtedly a tremendous field of research still open for the further development of aircraft electrical accessories. Those in the British electrical industry who have specialized in aircraft equipment are quite capable of meeting any challenge set by the aircraft industry.

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THE REIGNITION VOLTAGE CHARACTERISTICS OF FREELY RECOVERING ARCS

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SUMMARY

Advances in the knowledge of arc interruption have been achieved by simplifying the arc and its interruption condition, and studying the recovery of the arc free from the presence of restriking voltage. The arc investigated is a d.c. pulsed discharge of about 100 millisec duration burning freely between carbon electrodes. The reignition voltage of the arc at a given time after sudden interruption is obtained by pulsing with a unit function voltage. By varying the voltage magnitude a 50% reignition value is found, and by repeating at different delay times after interruption, full reignition characteristics have been obtained to an accuracy of within ±5%. Characteristics are given for 10–50 amp arcs in air, nitrogen, argon and hydrogen at pressures from 100 to 750 mm Hg, and with gap separations of 1–5 mm.

The results show that full recovery takes about 1 sec and that breakdown occurs in different forms. For delays of 0–100 microsec thermal breakdown occurs owing to the low resistivity of the decaying arc column and electrode regions. From about 0·1 to 1 sec true spark breakdown is observed. At intermediate times the breakdown is affected both by free charge and reduced gas density.

The spark breakdown voltages are found to follow closely an extended Paschen law, and give useful derived gas temperatures. A new phenomenon of a recovery pause is observed and is explained in terms of breakdown at the minimum spark voltage. The results also show the effects of energy exchange between gas and electrodes, and the improvement of recovery with current reduction and increased electrode mass. Only small differences are observed between the recovery of horizontal and vertical arcs. In general, the rapidity of recovery increases in the following order: argon, air, nitrogen and hydrogen.

(1) INTRODUCTION

When a circuit-breaker which is on load or carrying short-circuit current is operated, an arc discharge is inevitably drawn between the separating contacts. Even at low currents high gas temperatures are produced by such arcs. Thus a 20 amp carbon arc has a temperature[1] of about 6 000° K. Relatively few temperature measurements have been made on arcs in circuit-breakers, but the work of ter Horst and Rutgers[2] indicates that, in an air-blast circuit-breaker, a temperature of about 16 000° K is obtained at a 1 kA maximum of an alternating current. This temperature falls to about 12 000° K as the current decreases to zero.

An essential feature of circuit-breaking is thus the production of very high temperatures within the arcing chamber. These are sufficient to produce decomposition and chemical reactions in any gas or liquid insulating medium and also to vapourize the electrode material. It is also to be noted that the arc region is non-uniform, appreciable temperature and pressure gradients existing, and that, in a normal circuit-breaker, the arc duration is uncontrolled and the arc characteristics are affected both by the mode and velocity of contact separation. In an a.c. circuit-breaker any analysis of the arc properties must account for the dynamic changes which occur as the current decreases to zero.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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It will be appreciated that the many interrelated factors which have been mentioned make an accurate prediction of current-zero gap conditions almost impossible unless many simplifying assumptions are made. However, even if some acceptable analytic form of the dynamic arc properties could be obtained, the circuit-breaker problem would still only be partially solved.

Consider the known fact that, at current zero, high gas temperatures exist in the arc chamber. Then, owing to the high temperature, considerable but equal concentrations of electrons and positive ions exist in the gap, which contains considerable thermal energy. If, at zero current, the voltage supply is removed, any small dissipatory force which takes energy from the gap will reduce the gas ultimately to a non-conductive state. However, in a circuit-breaker such *free recovery* is not obtained, for at current zero the natural circuit voltage appears across the gap. The effect of the circuit voltage is to cause the free electrons and positive ions to be accelerated in the gap, and the phenomenon of post-arc conduction is observed. This flow of post-arc current produces an energy input into the gap which thus opposes the losses and can cause arc reignition. In order to determine the resultant gap energy we must set up a transient energy-balance equation and apply it to the post-arc period. Such an equation must include the many complex forms of energy loss which occur. Attention must also be given to the changes which occur at the electrodes and to the fact that, as the alternating current reverses, the electrode polarities also change. Naturally one should not consider the pre- and post-zero periods separately. Ideally one dynamic energy-balance equation in conjunction with the normal laws of transient electrical gas conduction and thermodynamics is sufficient to determine the resultant current conduction during both the pre- and post-zero periods if the boundary conditions are known. In view of the complexities described above, such an overall approach to the problem must meet almost insuperable difficulties, particularly since little is known at present about the precise manner in which the energy losses occur.

Despite these difficulties, valuable theoretical contributions with simplifying assumptions have been made by Slepian,[3] Cassie,[4] Mayr[5] and Browne.[6] Nevertheless the problem is still so complex that it is not yet possible to design a circuit-breaker and obtain the desired predetermined performance. Thus investigators have been forced to determine experimentally the interruption conditions, particular attention being given to the measurement of gap recovery, by a determination of the variation with time after current zero of the voltage required to break down the gap. The development of this type of measurement has been described fully by the authors.[7] Thus Slepian[3] and his colleagues, using a normal switch current, varied the rate of rise of restriking voltage to determine a recovery characteristic which is the envelope of restriking voltages which just allow interruption. Cobine[8] modified this method slightly by measuring the actual voltages at which breakdown occurs. We have defined free recovery above and in an earlier publication[9] as the gap recovery which occurs when no voltage is applied after current zero. A first step towards obtaining free recovery characteristics was made by Bauer and Cobine[10] by artificially extinguishing an

a.c. arc at a controlled time before normal current zero. By varying this time the normal circuit restriking voltage acted as a probe of the recovering gap. McCann and Clark,[11] and, later, McCann, Connor and Ellis,[12] improved the technique by using an a.c. arc source and a separate impulse-generator restriking source which could be applied to the gap at any instant after current zero.

Despite the valuable data which these investigators provided, the experimental conditions were far from simple. Thus, although the results give general indications of the properties of the recovering gap, they do not lead to a formulation of an interruption theory. In view of the intricacy and the history of the problem we believe that it would be a considerable advance if an interruption theory could be formulated which predicted experimental results, no matter how simplified the actual experimental conditions. Thus investigations were initiated in order to measure some important gap properties under free recovery conditions. The measurements being made are as follows:

(i) The recovery of gas temperature.
(ii) The recovery of electrical conductivity and hence the decay of free-charge concentration.
(iii) The recovery of gap breakdown-voltage strength.

The simplified conditions which have been chosen for the experiments are as follows:

(*a*) Fixed electrode gap, the arc being initiated by an auxiliary spark discharge.
(*b*) A d.c. arc, the current of which is reduced to zero in less than 1 microsec, thus giving well defined initial gap recovery conditions.
(*c*) Carbon electrodes, because of the reduced deterioration which occurs with these during tests.
(*d*) Low currents initially in order to reduce the amount of electrode vapour entering the arc.
(*e*) Relatively simple gases such as hydrogen, argon, nitrogen and oxygen.
(*f*) Free convective conditions, ultimately controlled loss condition, such as forced convection and convection-free conditions.

When sufficient data have been obtained under free recovery conditions, experiments will be conducted with a restriking voltage impressed at current zero. With these measurements and the free recovery data, it should be possible to determine whether a simple energy-balance formulation based upon, for example, conduction and convection losses only is sufficient to predict the interruption performance. Such experiments may indicate the importance of additional factors like turbulence.

The first experiments and development of technique in this programme were on the free recovery of breakdown-voltage. A technique for obtaining precise pulsed arc conditions was developed, and a delayed linearly rising probing voltage was used for obtaining the breakdown voltages. These experiments have been described by Kelham.[13] A major defect in this early work was the linearly rising restriking voltage used, since the recovery characteristic cannot be accurately determined unless the voltage pulse has a special form. Let us consider Fig. 1, which depicts an assumed true breakdown-voltage recovery characteristic having a sudden change in recovery rate, and assume a linear voltage pulse applied at t_1. Under these conditions a breakdown value at A should be given, but instead the breakdown value at B is obtained. Further, it is clear that the value at B′ can never be obtained owing to the prior breakdown at B. Consideration shows that, with this form of pulse, the portion of the curve between D and D′ cannot be measured. However, with a pulse of infinite rate of rise, every point on the curve can be obtained. Owing to statistical and formative time lags we cannot use such a high rate of rise without limiting the voltage. It is thus clear that a variable-magnitude unit function pulse is the ideal waveform for both accurate voltage breakdown

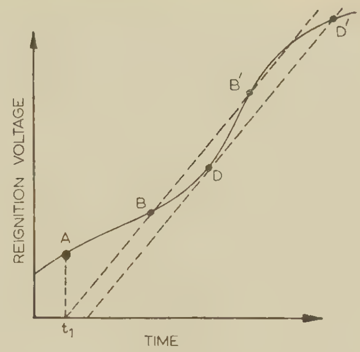

Fig. 1.—Reignition with linear probing voltage.
—— Assumed breakdown-voltage recovery characteristic.
– – – – Probing voltages.

measurements and full delineation of the characteristic. Since first proposing[9] this technique of measurement, Cobine, Burger and Farrall[14] have suggested that a fast linearly rising probe voltage is satisfactory, since statistical lags would not be expected to occur early in the recovery period. Whilst this may be so in the early post-arc period of heavy current arcs, our experiments show lags over a wide range of recovery time. The use of a unit function allows one to observe whether such lags exist and greatly improves the accuracy of measurement.

Since breakdown of a recovering gap can occur in different forms, and since also breakdown need not necessarily result in arc reignition, further consideration must be given to the definition of the reignition voltage and to the type of unit function source which will allow measurement over the full period of recovery. We therefore consider the main aspects of the free recovery of a gap.

(1.1) Free Recovery of a Gap

When the current of an arc is interrupted, the conditions which exist in the arc gap when current zero is reached depend upon the rate at which current reduction occurs. In our case, the interruption is sudden so that the gap properties will be initially those of the arc discharge immediately prior to interruption. In order to bring out some of the properties of the free recovery of an arc after sudden interruption we consider, as an example, the free recovery of a hydrogen arc, since, in this case, the gas properties are relatively simple and well known. Thus if we assume a decay of temperature of a low-current hydrogen arc after interruption as shown in Fig. 2, we can, assuming thermal equilibrium, plot the time-dependent variation of electron and ion concentration, molecular dissociation and gas density which will exist in the gap. With such a typical recovery plot, the occurrence of two widely different forms of arc reignition in the gas may be inferred, namely:

(i) Arc reignition via thermal breakdown.
(ii) Arc reignition via spark breakdown.

Thermal breakdown will occur in the immediate post-arc period when the free charge concentration is high and the gas density low. Under these conditions of high electrical conductivity any voltage applied to the gap produces immediate current conduction and energy input. If this energy input produces increased temperature and thermal ionization, and hence a reduction in resistivity, a cumulative growth of current may occur if the energy input is maintained at a value greater than the transient losses. Such a current growth terminating in arc reignition is defined as thermal breakdown.

Spark breakdown, on the other hand, will always occur in the final stages of recovery when the free charge is negligible

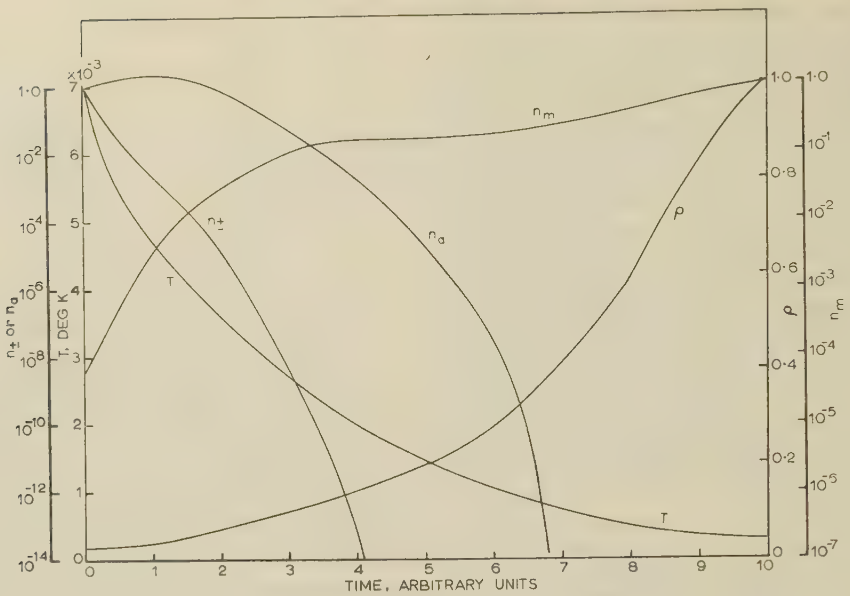

Fig. 2.—Free recovery of the properties of a suddenly interrupted hydrogen arc.

T = Assumed temperature decay.

Derived and normalized properties.
ρ = Gas density.
n_a = Atom concentration.
n_m = Molecular concentration.
$n_\pm$ = Positive ion or electron concentration.

and the gas density lower than the pre-arc value. It is not possible to specify a precise instant during the recovery at which the transition from thermal to spark breakdown will occur, for the processes are controlled in a complex fashion by the relative importance of discharge losses, free charge and electric-field configuration. Further, it is clearly possible in the thermal-to-spark breakdown transition period for arc reignition to be obtained after the onset of special discharge forms, e.g. by discharges having glow characteristics.

So far we have ignored the effects of the electrodes on the arc recovery, since Fig. 2 refers only to the recovery of the gas properties. The electrodes have an influence on the recovery by virtue of their heat content and capacity, and the consequent energy exchanges which take place with the gas. The electrodes also markedly affect the recovery by changes which can occur in the space-charge regions close to the electrode surfaces. Thus after arc interruption it is possible for the cathode space charge to be removed in less than 1 microsec by surface recombination. However, with refractory electrodes (carbon, tungsten, molybdenum) the hot electrode mass cools only slowly and a net negative space charge will be maintained by thermionic emission. Thus, for refractory arcs, reignition at the electrode is easily achieved at low voltages. For cold-cathode arcs (e.g. copper and mercury), the space charges are removed and the electrode regions can be reformed only by the application of at least the minimum sparking voltage, so that almost immediately after arc interruption (less than 1 microsec) voltage recovery to about 300 volts occurs. Clearly, in the latter case, the process of thermal reignition in the gas will be masked, except for very short times after current zero, by the spark breakdown required in the electrode regions. It is likely that, after the initial spark breakdown at the electrodes, the process of arc reignition will be essentially a thermal breakdown. However, with refractory arcs, a thermal-breakdown reignition in both the gas and electrode regions may be observed for appreciable times after current zero.

(1.2) Definition of Reignition Voltage

Clearly, when voltage is applied to a recovering gap, many forms of conduction and breakdown can occur. In particular, transient currents may flow which do not result in final arc reignition. Therefore, in order to specify the conditions of measurement, we determine, as the reignition voltage, that voltage which produces full arc reignition of the gap, independent of the form which the reignition may take. However, since, during thermal breakdown, current conduction can produce distortion of the applied voltage waveform, we specify the use of a constant-voltage generator. We thus define the reignition voltage as follows:

> The gap reignition voltage is the lowest voltage of a constant-voltage generator, which, when connected instantaneously across a gap, causes an arc discharge to be formed.

With a true constant-voltage generator, arc reignition cannot be detected by voltage collapse across the gap, but only by current measurement. This is particularly important in the thermal-breakdown region, where the course of the current variation must be measured. However, in the spark-breakdown region, the pre-breakdown currents are small so that a generator having a small but appreciable internal impedance may be used, and reignition is then observed by the sustained voltage collapse across the gap. For the experiments described in the paper we have adopted this latter form of apparatus and measurement. The recovery of the first 100 microsec after current zero was not observable owing to the high electrical conductivity and consequent thermal breakdown. A separate investigation of this region is proceeding using a true constant-voltage generator and measuring current, charge concentration and temperature decay.

Thus, under the simplified experimental conditions described and with a unit-function impulse generator, free recovery characteristics have been obtained for arcs in air, nitrogen, argon and hydrogen at currents from 10 to 40 amp with gap

lengths of 1, 3 and 5 mm at pressures of 100–750 m Hg. The effects of electrode mass and orientation are also shown. These characteristics show all the main features of the recovery of refractory-electrode low-current arcs. As distinct from previous investigations, the results give the full course of the recovery of reignition voltage from close to the arc burning voltage up to the fully recovered value.

(2) EXPERIMENTAL TECHNIQUE AND APPARATUS

The essentials of the technique for forming the d.c. arc pulse and unit-function probing voltage prescribed by the experimental conditions in Section 1 are given in Fig. 3. Thus, in Fig. 3(*a*),

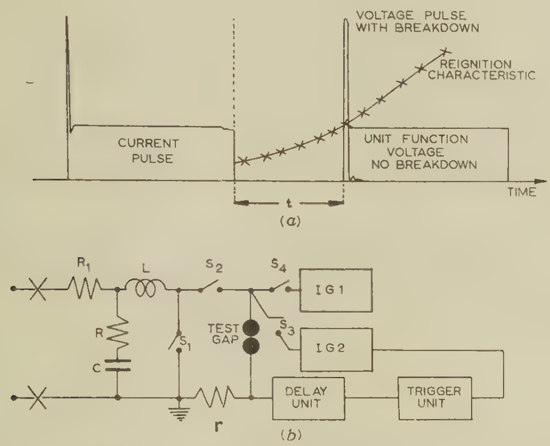

Fig. 3.—Experimental arrangements.
(*a*) Basic technique for reignition-characteristic determination
(*b*) Basic diagram of circuit used.

a rectangular current pulse is formed across fixed electrodes, and the gap is allowed to recovery freely for a time *t*. At this instant the unit-function voltage is applied, and oscillographic observation indicates whether reignition has occurred. A number of tests are made at this instant with variation in the amplitude of the probing voltage. The voltage at which reignition occurs for 50% of the tests is taken as the reignition voltage. In this way, account is taken of the variation in reignition voltage due to uncontrolled fluctuations in the experimental condition. We found that about 50 tests must be made in order to obtain one 50% reignition-voltage value. Series of 50 tests were then made at differing delay times in order to obtain one free-recovery characteristic.

In order to reduce scatter in results the electrodes were carefully cleaned, first by mechanical means and then by electrical bombardment *in situ* in a hydrogen high-pressure glow-discharge tube (50 mA at 50–100 mm Hg). The electrical cleaning was continued for about one hour, during which time the polarity of the glow was changed several times. Surface contaminants were thus removed and only a few subsequent arc tests were sufficient to produce an electrode system which gave consistent results. Spectroscopic carbon was used for the manufacture of the electrodes, and commercially pure gas, after drying, was used in the experiments. The test chamber was a 4 in-diameter glass cylinder 6 in long and fitted with electrode holders connected to adjustable bellow seals. Using micrometer heads, the electrode separation could be accurately adjusted.

(2.1) Arc-Current Waveform

In Fig. 3(*b*) the switches S_1 and S_3 are initially open, and S_2 and S_4 are closed. The arc is initiated between the fixed electrodes by a high-voltage impulse from the impulse generator IG1, the d.c. source being protected by the *RLC* filter. The theory of this method of initiation has been described.[15] The current from the d.c. supply is set by the resistor R_1. The arc is maintained for a period long enough for convective equilibrium to be reached (about 100 millisec) during which the current is constant to within $\pm 2\%$. After 100 millisec the arc is interrupted rapidly (about 1 microsec) by short-circuiting the gap by S_1. One or two milliseconds before S_1 closes, S_2 opens, causing a reduction of about 5% in the current, and S_3 closes, connecting the probe-voltage source IG2 to the gap. In order to ensure that the probing voltage does not break down the gap S_2, the switch S_2 is blown by a high-pressure air blast.

(2.2) Probing-Voltage Waveform

The unit-function generator prescribed in Section 1.2 is shown as IG2 in Fig. 3(*b*). The voltage source used was a $0\cdot 02\,\mu$F low-inductance capacitor with a 300-kilohm wavetail resistor. A wavefront resistor of 615 ohms was used and the test-gap stray capacitance was 76 pF. With this unit a voltage pulse rising to 98% of maximum was obtained in $0\cdot 3$ microsec, and the maximum value was maintained to within 1% in the succeeding 100 microsec. The regulation of the unit was such that breakdown was observable from 100 microsec delay without distortion due to pre-breakdown currents.

(2.3) Delay and Triggering Units

Application of the probing voltage is controlled by an electronic delay unit having an input discriminator stage operating on the sudden fall in voltage across the resistance *r* [Fig. 3(*b*)] when arc interruption occurs. The pulse obtained from the discriminator is passed to a monostable multivibrator section giving an output pulse with easily controlled delay. After amplification this pulse is applied to a hydrogen tripping circuit which initiates the probing-voltage generator.

With this circuit, a scale of logarithmically spaced delay times ranging from 40 microsec to 800 millisec was available with negligible jitter.

(2.4) Measurements

The probing-voltage transient presents two quantities to be measured or examined, namely the amplitude and waveform. If the transient is applied to a distortionless voltage divider and the signal from an output tapping is applied to a high-speed oscillograph, calibrated with the divider, it is possible to satisfy both requirements simultaneously. In these tests, however, temporal measurements were not required, and from the nature of the restriking-voltage waveform a simpler and equally suitable method of amplitude measurements is available. The amplitude of the step function supplied by IG2 was obtained by the use of a d.c. voltage divider connected to measure the voltage to which the impulse capacitor forming its output element is charged. The transient was viewed to determine whether reignition occurs or not, using an uncalibrated distortionless voltage divider with the high-speed cathode-ray oscillograph. Thus the heavy labour of photographic recording and measurement was avoided.

The voltage divider used to measure the probing-voltage amplitude consisted of one hundred 1-megohm high-stability carbon track-type resistors wound in a helix on flat Paxolin formers embedded in wax. It is estimated that the overall errors of the voltage divider and the electrostatic voltmeter used with it did not exceed $\pm 3\%$ over the range 220 volts–33 kV for the output of IG2.

The voltage divider for displaying the transient had an upper arm consisting of six 100 pF 10 kV capacitors, each shunted by

a 4·7-megohm resistor. Bottom-end capacitors and resistors were chosen to have the same time-constant, and to cover an adequate range of voltage division. To prevent the waveform supplied by IG2 from being affected by the presence of this divider the capacitances have been made low. Measurements indicate an addition of only about 25pF above the gap stray capacitances when the voltage divider is connected in circuit.

(2.5) Sequence Control

Except for the probing-voltage initiation, the timing of events occurring during the experimental cycle was controlled by a rotary cam system, which fulfilled the following functions.

(*a*) *Sequence Control.*—To prevent the system from rotating continuously, the mains supply to the driving motor is taken via contacts which may be short-circuited by a pushbutton or closed by a cam. To start a cycle, the button is pressed until the cam closes the contacts. The system then rotates through about 330° until the contacts open again.

(*b*) *Circuit-breaker closing.*—The main d.c. supply circuit-breaker is closed by a cam operating contacts connected in series with its hold-in coils.

(*c*) *Arc initiation.*—During the cycle contacts close to trip the arc-initiating impulse generator IG1.

(*d*) *Delay-unit protection.*—Considerable difficulty was experienced during development of the experimental technique by spurious tripping of the delay unit when IG1 fired. This is avoided by short-circuiting the input stage by contacts timed to remain closed for a short period during which IG1 is triggered.

(*e*) *Arc interruption.*—The main switch, S_1, used to obtain the trailing edge of the current pulse is spring loaded and is tripped by a solenoid-operated striker pulled in when a cam operates contacts in series with its supply. S_2 and S_3 are ganged to the switch respectively opening and closing a little before the current chopping occurs.

(3) EXPERIMENTS AND RESULTS

(3.1) Preliminary Experiments and Observations

A preliminary investigation was made to determine the experimental conditions which gave the greatest accuracy in results without undue labour. It was known from previous work that dry gases and spectroscopically pure electrodes, mechanically and electrically cleaned, were required for consistency in results. It remained to determine the accuracy obtainable with different combinations of electrode material and gas. Experiments confirming earlier work indicated that the surfaces of both copper and tungsten electrodes are rapidly and markedly altered by arcing, spikes and craters being formed. These irregularities produce appreciable changes in the recovery breakdown voltage, and thus with these materials, the production of recovery characteristics involves constant changing of the electrodes. However, experiments with carbon electrodes showed that approximately 100 arcing tests could be made without undue deterioration of the electrodes. Further, since, with this material, the arc produces a hot electrode system, the recovery processes are slowed down initially and interchanges of gap and electrode energy become more readily measurable. For these reasons the recovery characteristics showing the influence of the variation of the main parameters, such as current, pressure, gap length and electrode mass, have been determined using carbon electrodes, and are described in the paper. Plain-ended cylindrical electrodes were selected and were made small (4 mm diameter) in order to improve localization of the discharge and hence reduce scatter in the results.

Electrode deterioration is influenced by the amplitude and duration of the current pulse. At currents between 10 and 40 amp a duration of about 100 millisec was chosen, since it was found that convective equilibrium is approached closely within this time.

For greatest ease in testing, a gas should be used which is not affected by the discharges, has low arc burning voltages, and low thermal conductivity. These quantities reduce the frequency with which the chamber must be refilled during testing, they decrease the rate of deterioration of the electrodes and slow down the recovery rate. Such a gas is argon, which was employed for most of the testing. The ease with which reproducible results could be obtained decreased in the order of argon, hydrogen, nitrogen, air, with air being very much worse than the other gases. For argon, hydrogen and nitrogen the reproducibility is such that the estimated accuracy of the curves given is $\pm 5\%$. With air, however, the accuracy is estimated to be $\pm 10\%$. The smoothness of the curves suggests that these estimates are pessimistic. The accuracies given refer to the 50% reignition values. It is noteworthy that, in our experiments, the variation about the 50% value was of the order of $\pm 15\%$. With this technique, however, greater accuracy can always be achieved by increasing the number of tests at a given delay time.

(3.2) Results and Reignition Recovery Characteristics

The reignition transients observed oscillographically had the common features exhibited in Fig. 4 in all gases in which experiments were carried out. At long times after arc interruption spark breakdown occurs [Fig. 4(*a*)]. At shorter times, when there may be appreciable residual electrical conductivity, breakdown is slower [Fig. 4(*b*)]. In some cases a continuous breakdown which approaches the condition of thermal breakdown has been observed [Fig. 4(*c*)].

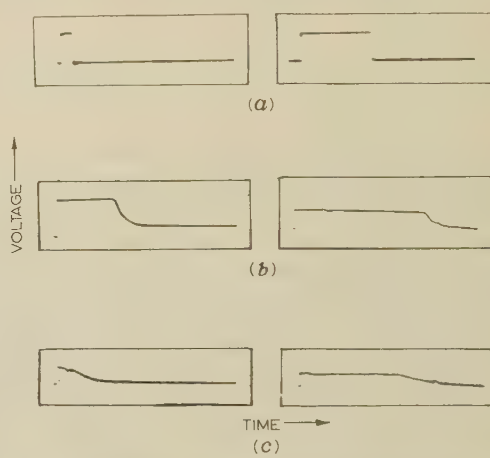

Fig. 4.—Typical oscillograms of reignition with unit-function probe voltage.

(*a*) Spark-type breakdown.
(*b*) Slow breakdown.
(*c*) Continuous breakdown.

(3.2.1) Recovery Characteristics in Air.

Characteristics were obtained for a 20 amp 100 millisec arc for different pressures and gap spacings. These results are shown in Fig. 5, plotted on a logarithmic scale.

It was found to be exceedingly difficult to obtain consistent results, and it was necessary to change the gas frequently, presumably to avoid the accumulation of discharge products such as CO_2, NO_2, etc.

The electrodes deteriorated rapidly, the anode being rounded off while a crater developed in the cathode, so that electrode replacement was necessary after every 50–60 discharges.

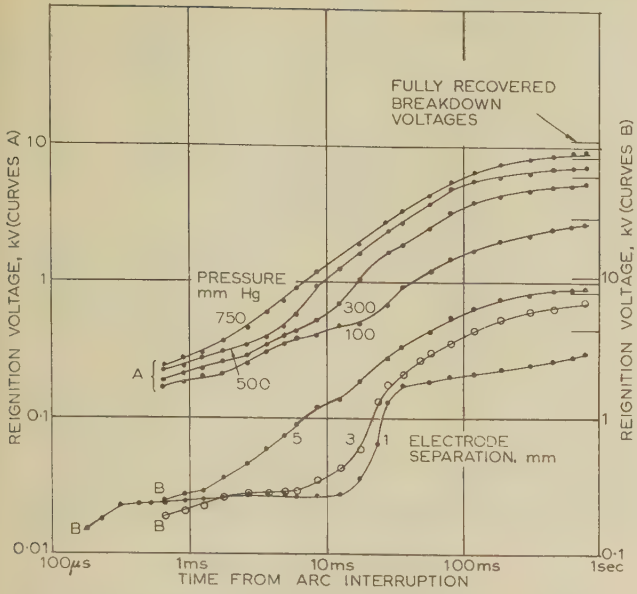

Fig. 5.—Reignition voltage characteristics for air. Variation of pressure and electrode separation.

Arc-current = 20 amp.
Duration = 100 millisec.
Electrodes: carbon 4 mm diameter.
A. 5 mm electrode separation.
B. 750 mm Hg pressure.

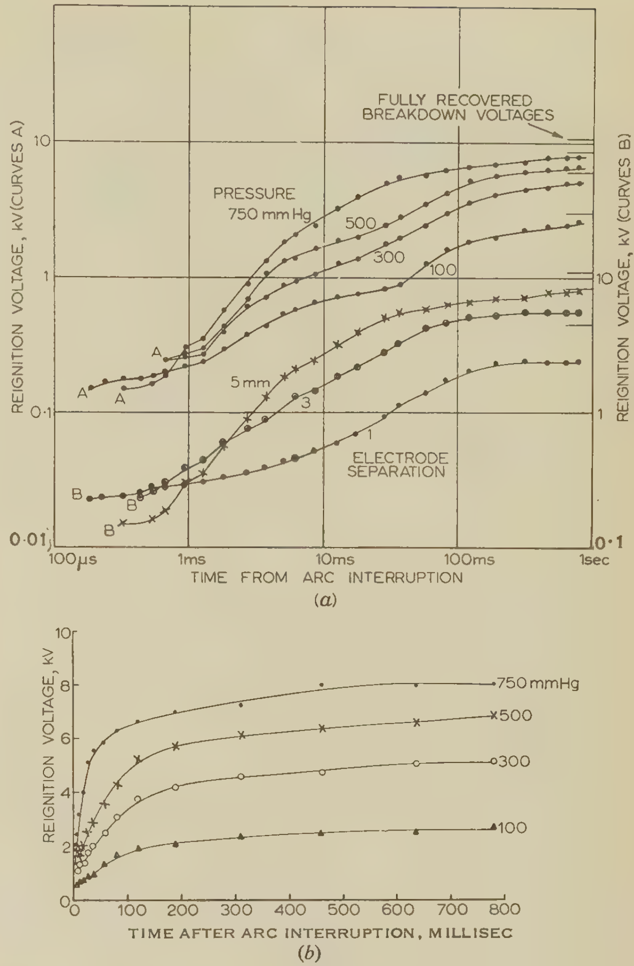

Fig. 6.—Reignition voltage characteristics for nitrogen. Variation of pressure and electrode separation.

Arc current = 20 amp.
Duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
A. 5 mm electrode separation.
B. 750 mm Hg pressure.
(a) Logarithmic plot.
(b) Linear plot.

(3.2.2) Recovery Characteristics in Nitrogen.

A set of curves similar to those obtained in air were obtained for nitrogen and are shown in Figs. 6(*a*) and (*b*). After electrical cleaning, results were obtained with much greater consistency. Deterioration of the electrodes was much slower, 150–200 discharges being possible before replacement. Although the anode tended to become rounded off, as in air, the cathode became covered with a large number of small craters.

(3.2.3) Recovery Characteristics in Argon.

It was found that very consistent results could be obtained in argon, so that, after obtaining a set of curves (Fig. 7) similar to those obtained in air and nitrogen, the influences of several other factors were examined. Figs. 8 and 9 show families of curves obtained by varying the arc amplitude and duration over the ranges 10–40 amp at 100 millisec duration, and 50–200 millisec at 20 amp.

Fig. 10 shows the influence of electrode diameter on the recovery of a 1 mm gap, and Fig. 11 indicates the effects of gap orientation for 3 and 5 mm gap spacings.

Deterioration of the electrodes was very slow. Both anode and cathode showed rounding and became smoothly polished.

(3.2.4) Recovery Characteristics in Hydrogen.

The recovery curve (Fig. 12) obtained in hydrogen was obtained with greater ease and consistency than the corresponding curve in nitrogen. This may be attributable to greater purity of the gas used and to self-cleaning of the electrodes. Deterioration of the electrodes was more rapid than in nitrogen, several craters developing in the anode, while the cathode became roughened.

Limitations of the delay circuit precluded extension of the recovery characteristic below the pause voltage of 215 volts.

(3.3) Normal Breakdown Voltages

Full recovery has been attained when the reignition voltage is equal to the normal breakdown voltage of the gap. These values were measured using a high-voltage d.c. supply and the calibrated voltage divider described in Section 2.4. They are plotted on their appropriate curves for air, nitrogen and hydrogen. Tests in argon indicated rather higher values if breakdown voltages were measured using IG2. This is probably due to the long time lags which obtain in argon.

(4) DISCUSSION OF RESULTS

Examination of the reignition recovery characteristics given in Figs. 5–12 shows several important and general features of the recovery which are obtained under our experimental conditions. First, it will be observed that the time required for full recovery is about 1 sec, and that the characteristics give the course of recovery from voltages close to arc voltages up to the fully recovered normal breakdown values. The long period of recovery is obtained since only natural convection, conduction and radiation losses are effective in reducing the system to the pre-arc state. Further, the use of carbon electrodes which have a relatively low thermal conductivity and which are brought to a high temperature by the arc, also prolong the recovery period. Naturally, if forced convection were applied, the

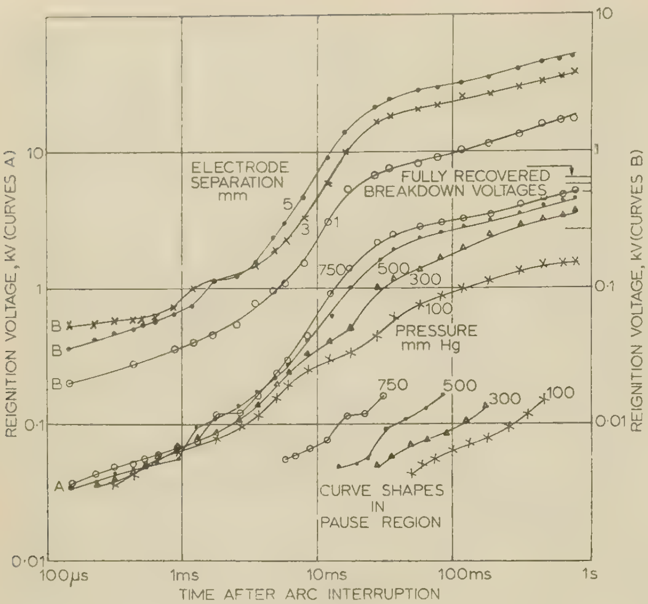

Fig. 7.—Reignition voltage characteristics for argon. Variation of pressure and electrode separation.

Arc current = 20 amp.
Duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
A. 5 mm electrode separation.
B. 750 mm Hg pressure.

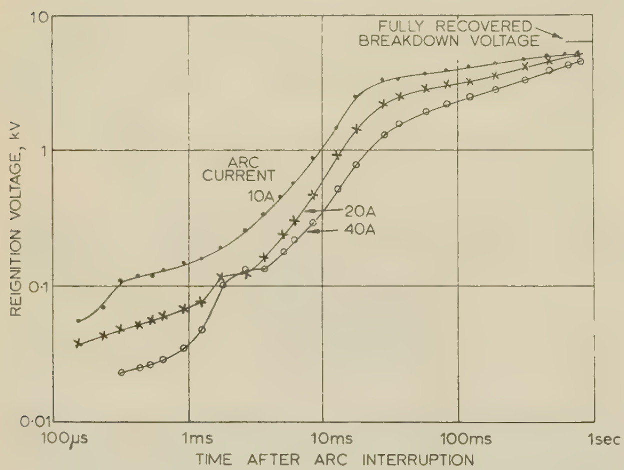

Fig. 8.—Reignition voltage characteristics for argon. Variation of arc current.

Arc duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
Pressure = 750 mm Hg.
Electrode separation = 5 mm.

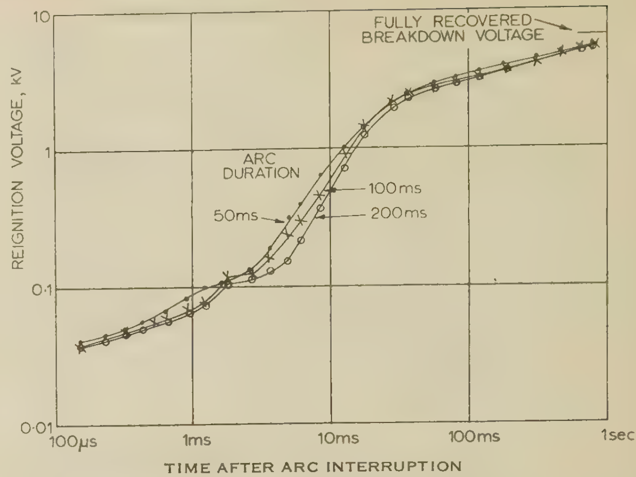

Fig. 9.—Reignition voltage characteristics for argon. Variation of arc duration.

Arc current = 20 amp.
Electrodes: Carbon 4 mm diameter.
Pressure = 750 mm Hg.
Electrode separation = 5 mm.

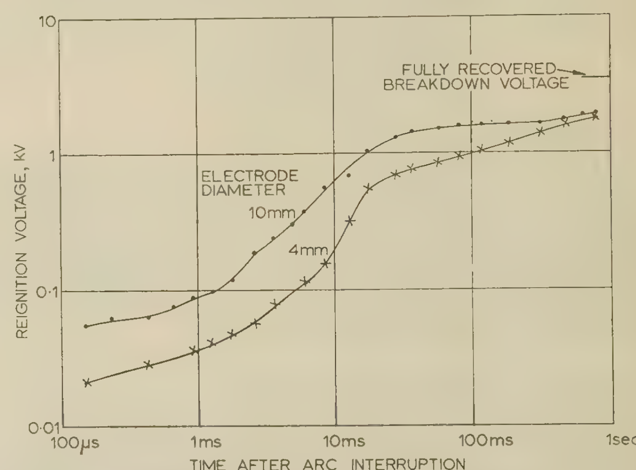

Fig. 10.—Reignition voltage characteristics for argon. Variation of electrode diameter.

Arc current = 20 amp. Duration = 100 millisec.
Electrodes: Carbon.
Pressure = 750 mm Hg.
Electrode separation = 1 mm.

recovery period would be markedly reduced. Experiments on this effect are proceeding. Under present conditions the long recovery period enables us to separate many of the individual recovery effects. In order to show the varied nature of the characteristics, the curves are plotted logarithmically. However, in Fig. 6(*b*) a linear time plot is given of the nitrogen characteristics. This shows a further general feature of the characteristics, namely that, in approximately the first 100 millisec, a rapid rise in recovery occurs followed by a long period of relatively slow final recovery. A similar feature has been observed by Cobine *et al.*[8] It will be shown later that this final recovery is associated with spark breakdown during the final decay of the gas temperature. During the initial 100 millisec of recovery, experiments by Allan and Edels* show that the gas temperature falls from 6 500° K to about 1 000° K. Thus it is to be expected that during this period the major part of the recovery will occur, owing to the marked increase in gas density, the disappearance of free charge and the cooling of the electrodes. This will be followed by a slow recovery whilst the gas temperature slowly decays from about 1 000° K to room temperature. The temperatures given are only indicative of the type of value obtained during our experiments, but the explanation may probably be suitably applied to describe the results of Cobine and others.

A further common feature of the characteristics given in Figs. 5–12 is the evidence of a pause in the recovery. For example, in Fig. 5 the curve for the 1 mm gap in air at 750 mm Hg shows a remarkable pause in the recovery during the period 320 microsec–12·6 millisec, when the reignition voltage rises only from 221 to 267 volts. There appears to be a com-

* To be published.

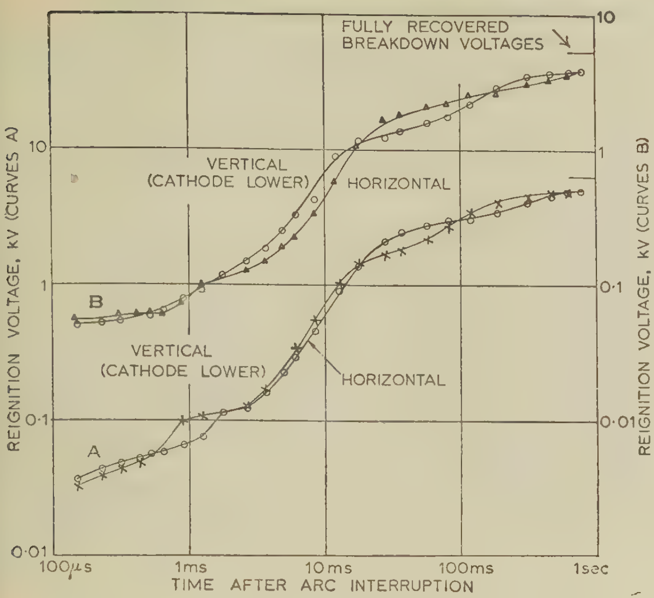

Fig. 11.—Reignition voltage characteristics for argon. Influence of electrode orientation.

Arc current = 20 amp. Duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
Pressure = 750 mm Hg.
A. 5 mm electrode separation.
B. 3 mm electrode separation.

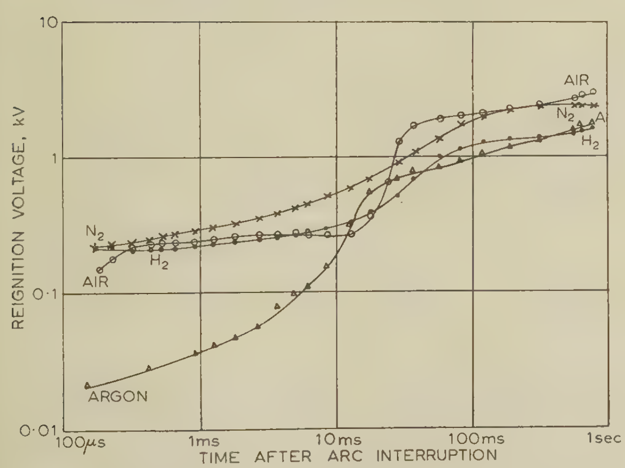

Fig. 12.—Comparison of reignition voltage characteristics in different gases.

Arc current = 20 amp. Duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
Pressures = 750 mm Hg.
Electrode separation = 1 mm.

plete cessation of recovery at 267 volts during the period 2·64–12·6 millisec. Although the pauses for other experimental conditions are not all as long as this, the evidence which will be discussed suggests that the pauses are associated with the phenomenon of minimum spark breakdown. Finally, detailed examination of the characteristics indicates that a marked energy exchange occurs between the electrodes and gas, and that the recovery is largely dependent upon the thermal conditions of the system. This evidence is discussed in detail in Section 4.2.

(4.1) Properties of the Recovery

(4.1.1) Thermal Breakdown Period.

In accordance with the considerations of Section 1.1 and 1.2, reignition voltage measurement is not possible in the thermal-breakdown period if a pulse generator of finite impedance is used. However, with a low-impedance generator, measurement first becomes possible when reignition is shown by a slow decay of the applied probe voltage. These 'slow breakdowns' [Fig. 4(*b*)] will first occur at a time after interruption dependent upon the generator impedance and the decay of gap electrical conductivity. If the conductivity is essentially controlled by thermal factors we would expect some correlation between the first appearance of 'slow breakdown' and gap cooling. Such a correlation exists, for we note that 'slow breakdowns' first become measurable at 43, 908 and 1 250 microsec for the 1, 3 and 5 mm gaps in air and at 43, 433 and 908 microsec for corresponding gaps in nitrogen. This indicates that the closer proximity of the electrodes causes enhanced cooling of the gas and produces a relatively more rapid recovery and decay of free charge and electrical conductivity.

In all cases the initial 'slow breakdown' voltages are less than the glow cathode voltage to be expected for the given discharge conditions. Indeed, in the case of argon, the initial values are about 30 volts, thus closely approaching arc voltages. The results indicate that, for the thermionic-type arc being investigated, a slow recovery of reignition voltage occurs from the arc voltage at $t = 0$ up to the recovery pause voltage at about 100 microsec. This slow rise in reignition voltage is quite different from the well-known 'instantaneous recovery' to the glow-cathode fall voltage which is obtained with cold-cathode arcs (copper and mercury) and which is associated with the rapid formation (less than 1 microsec) of a neutral sheath around the cathode surface. Our results are due to the maintenance of a high carbon cathode temperature for appreciable periods (greater than 100 microsec), which allows the easy re-establishment of thermionic emission on the application of a probing voltage. As the electrodes and gas slowly cool the voltage required for the production of arc emission at the cathode and arc reignition in the gas will slowly rise.

Ultimately the electrodes will cool to a temperature at which thermionic emission becomes negligible and at which a neutral sheath can be formed and maintained by surface recombination. After this instant reignition can occur only after prior breakdown and glow formation in the cathode sheath. As with cold-cathode arcs, despite the still relatively high electrical conductivity of the gas column, current cannot flow without at least the application of the glow voltage. The spark-to-thermal type breakdown which ensues can first occur at the minimum spark voltage, and it is this phenomenon which, it is believed, is observed in the period of recovery pause.

(4.1.2) Recovery Pauses.

The pauses shown in the recovery characteristics have never been clearly observed previously, although there are some indications of their existence in the work of Bauer and Cobine[10] and Kelham.[13] Our results show that the pauses always occur at definite voltages which depend only on the gas used, carbon electrodes being used throughout. In argon the pause voltage is constant at 115 volts for currents of 10–40 amp. Similarly in air a constant voltage of 270 volts is obtained both for 1 and 3 mm gaps. The pause voltages obtained are

Hydrogen	215 volts
Air	270 volts
Nitrogen	230 volts
Argon	115 volts

These values are close to the glow cathode-fall voltages which may be expected for these electrode-gas combinations and lead us[9] to suggest that the pauses are produced by the continued breakdown of a neutral cathode sheath at the minimum spark breakdown voltage. The sheath is formed with carbon electrodes only after an appreciable period of full thermal breakdown.

The minimum spark breakdown voltage is the value which is given by the minimum in the Paschen law curve relating values of pd to spark-breakdown voltage, where ρ is the gas density and d is the gap separation. Paschen's law is normally determined and stated for a plane parallel uniform field configuration. However, provided that similarity in the field distribution is preserved, the law may be extended to any electrode geometry, although the minimum voltage measured will not be that of the uniform field case. We therefore suggest that, as recovery proceeds, the uncharged cathode sheath first breaks down at the minimum sparking voltage V_m, consistent with a definite value of $\rho d = \rho_0 d_0$, say. The Paschen curves show that, for $\rho d < \rho_0 d_0$, a higher breakdown voltage is required. Thus, since the sheath can initially have $\rho d < \rho_0 d_0$ and can cool non-uniformly spatially, it is possible to maintain breakdown at V_m for appreciable periods, for new paths of $\rho_0 d_0$ will constantly be produced. An important extension of the pause time can be produced by energy being fed into the cathode sheath from the hot gas, thus maintaining the required value of $\rho_0 d_0$. In this argument we have assumed that the reignition voltage of the remainder of the gap is small compared with V_m and that it remains essentially constant over the pause period. This is not always so, and it is possible for the gas to recover rapidly and dominate the recovery so that the pause is not observable. This phenomenon is probably the reason for the disappearance of the pause with increase in gap length for air and nitrogen. Argon, however, exhibits a different behaviour in this respect. Thus Fig. 7 shows that, for the 1 mm gap, no pause is obtained, but it becomes noticeable in the 3 mm case and more pronounced for the 5 mm curve. This anomalous characteristic probably indicates the influence of energy exchange between gas and electrode. It is noteworthy that the thermal conductivity of argon is less than that of the other gases. It is possible for a 1 mm gap in argon that the energy content of the gas is small compared with that of the electrode assembly. In this case the gas will recover rapidly, as shown by the normalized curves. However, as the gap length is increased, the total energy content increases, but, owing to the low gas thermal conductivity, the heat losses from the column are mainly restricted to exchange with the electrodes. Thus the electrodes accept energy from the gas and it is possible for the pause to be maintained without great changes in the column properties. Thus, with increase in gap the pause will become apparent.

Since little data were available on the minimum spark-breakdown and cathode-fall voltages obtaining under our conditions, experiments were made to determine them.[16] The values obtained, compared with the pause voltages, are given in Table 1.

Table 1

	Hydrogen	Nitrogen	Air	Argon
Cathode-fall voltage	216	330	335	205
Minimum spark and breakdown voltage	300	328	350	220
Pause voltage	215	230	270	115

The Table shows that the pause voltage is 60–100 volts lower than the cathode-fall voltage. However, the cathode-fall and spark-voltage measurements were made on clean electrodes and in gases free from carbon vapour and carbon combustion products, which will certainly exist in the recovering arc column. Some credence is given to this view by the good agreement in the case of hydrogen, for this gas was spectroscopically pure and arc operation automatically cleans the electrodes. Further experiments are required before the suggested explanation for the recovery pauses can be fully substantiated. Nevertheless, it is difficult at present to find a more reasonable explanation.

(4.1.3) Spark-Breakdown Period.

The breakdown in the recovery period immediately following the pauses will be affected by the low gas density and also the presence of considerable ionization. It cannot, at present, be analysed. However, when the temperature has fallen to about 2000° K thermal ionization will be negligible, and it may be expected that breakdown will then be a function solely of gas density and gap length. This view is supported by examination of the characteristics, which show that, for $t > 100$ millisec, the reignition voltage curves can be normalized for both pressure and gap separation to within $\pm 15\%$. The empirical formulae representing the characteristics give the reignition voltage as

$$V = f_1(t)f_2(p)$$

and

$$V = f_1(t)f_3(d)$$

within the range $100 < t < 800$ millisec; $100 < p < 750$ mm Hg (5 mm gap); $1 < d < 5$ mm (750 mm Hg).

The functions obtained are given in Table 2.

Table 2

NORMALIZED REIGNITION VOLTAGE FUNCTIONS

	Air	Nitrogen	Argon
$f_1(t)kV$	$t = 100$ millisec	$p = 750$ mm Hg	$d = 5$ mm
	$6 \cdot 2t^{0 \cdot 22}$	$6 \cdot 5t^{0 \cdot 11}$	$3 \cdot 0t^{0 \cdot 27}$
$f_2(p)kV$	$p = 100$ mm Hg	$d = 5$ mm	
	$0 \cdot 29p^{0 \cdot 63}$	$0 \cdot 31p^{0 \cdot 58}$	$0 \cdot 34p^{0 \cdot 53}$
$f_3(d)kV$	$p = 750$ mm Hg	$d = 5$ mm	
	$0 \cdot 32d^{0 \cdot 70}$	$0 \cdot 33d^{0 \cdot 69}$	$0 \cdot 36d^{0 \cdot 63}$

The satisfactory manner in which these functions represent the characteristics indicates that, in the last stage of recovery, reignition is by true spark breakdown. Since the electrode geometry does not remain similar with gap change we would not expect Paschen's law to be obeyed exactly. However, the results indicate that reignition in the spark period closely follows an extended Paschen law given by

$$V = kf(t)(pd)^n$$

(4.1.4) Temperature Recovery Characteristics.

If Paschen's law is obeyed in the spark period, then, for a given gap, the reignition characteristic will depict solely the manner in which the gas density recovers with time. The gas density appropriate to each reignition voltage may be determined by experiments with the gap in an un-arced condition. Thus with a set gap the variation of d.c. spark-breakdown voltage with change in gas pressure may be determined at room temperature. For a given reignition voltage V_R the recovered gas density ρ_R equals the test gas density, which gives a d.c. breakdown voltage, V_R. Thus, by setting the densities in terms of

the gas pressure and temperature, we are able to derive a recovered gas temperature, T_R, as

$$T_R = \frac{P_R}{P} T$$

where P and T refer to the d.c. test conditions and P_R is the gas pressure of the recovery tests.

This method of temperature derivation assumes a uniform gas density in the recovery arc column and that no post-discharge effects such as carbon vapour or combustion products affect the results. It is also assumed, since the recovery tests are made with impulse voltages, that the impulse ratio is unity. In our tests we found that only the impulse ratio of argon differed appreciably from unity, so that the recovery temperatures for this gas were determined using impulse breakdown conditions. By determining the direct and impulse breakdown voltage variations with pressure we have derived the temperature recovery characteristics shown in Figs. 13(a) and (b). The temperatures are in reasonable agreement with actual measurements made by shock-wave techniques.

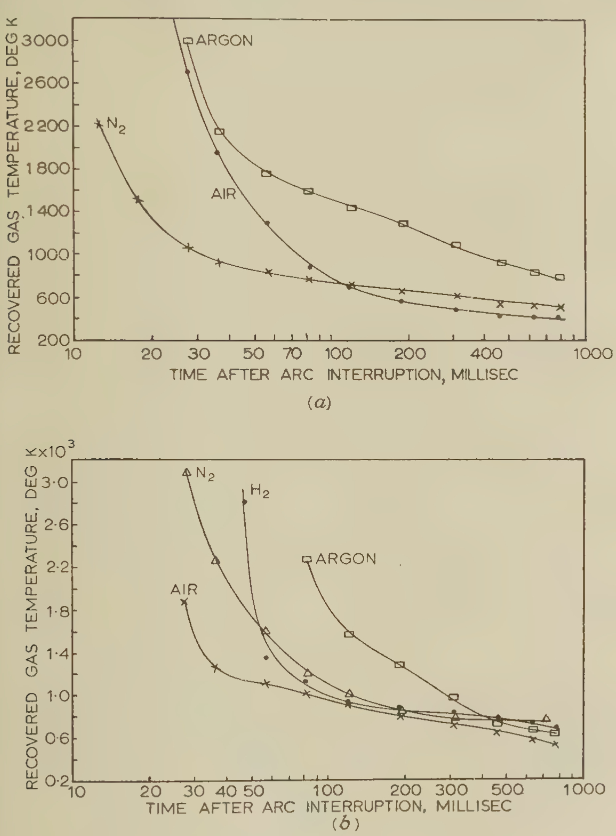

Fig. 13.—Derived temperature recovery characteristics.

Arc current = 20 amp. Duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
Pressure = 750 mm Hg.
(a) Electrode separation = 5 mm.
(b) Electrode separation = 1 mm.

(4.2) Energy Exchange in the Gap

The effects of electrode-gas energy exchange upon the appearance of the recovery pause has already been noted. There is further clear evidence of these energy flows in the recovery characteristics. Thus, in all gases, the results show that in the early recovery period the small gaps recover more rapidly. This is due to the enhanced gas cooling produced by the proximity of the electrodes, and has been observed by many investigators. When the gas temperature has decreased to that of the electrodes, it is likely that a reversal in the energy flow will occur since the heat content of the electrodes is so large. If so, we may expect the recovery of small electrode gaps to be delayed. This is shown in Fig. 14, which gives the reignition voltage as a percentage of the finally recovered value.

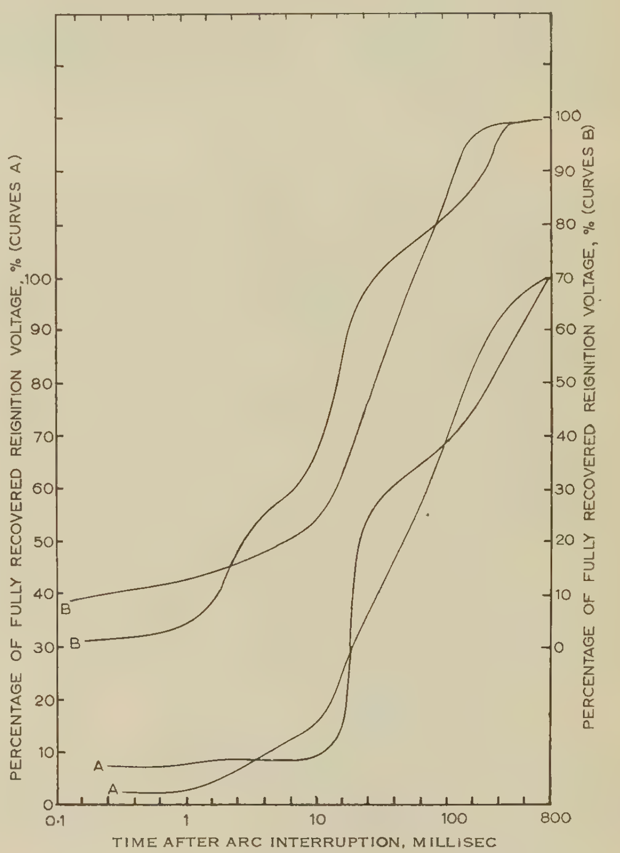

Fig. 14.—Percentage recovery characteristics.

Arc current = 20 amp. Duration = 100 millisec.
Electrodes: Carbon 4 mm diameter.
Pressure = 750 mm Hg.

The gas-electrode energy flow is also clearly exhibited by the results of Fig. 10. With the small gap spacing, the larger electrode diameter and mass produces an enhanced cooling and recovery over the whole recovery period. Electrode orientation, which obviously affects the energy flow, does not under our conditions appear to be of great importance (see Fig. 11). This is presumably due to the relatively low currents used and the consequently low convection velocities.

(4.3) Effects of Discharge Conditions

Families of characteristics are obtained with variation of pressure, as shown in Figs. 5, 6 and 7. In the spark stage of recovery, as noted, the curves may be normalized. In the early recovery periods (less than 1 millisec), the percentage of full recovery indicate that it is a little more rapid at the lower pressures.

Fig. 8 shows the delayed recovery produced by increase in arc current, with a gradual convergence to the same fully recovered reignition voltage. Despite the effects of current magnitude, the pauses occur at the same voltage. The results of Fig. 9 show the relatively small changes produced by variation

in arc duration of 100–200 millisec, indicating that, with these arc durations, convective equilibrium is approached.

Comparison of the characteristics for different gases show that, under given conditions, the rapidity of recovery increases in the following order: argon, air, nitrogen and hydrogen. For example, at 750 mm Hg, 5 mm gap and 6 millisec delay the percentage recovery of the first three of these gases is 5·8, 9·7, 24·8%. These values are, of course, not constant with time. Variation in gap spacing has an influence on the relative gas recoveries, although the general order of recovery is not completely altered. In particular, as the gap is reduced, the recovery of nitrogen and air is affected more than that of argon.

(5) CONCLUSIONS

Recognizing the complexity of the problem of circuit-breaking, the conditions of arc interruption have been reduced to especially simple and accurately controllable forms. Experiments under these conditions have given data on the free recovery of suddenly interrupted d.c. arcs and have successfully shown the existence of several distinct periods of recovery. In particular, the new phenomenon of recovery pause has been exhibited and the existence of electrode-gas energy flows has been established. In order to describe more fully the recovery phenomena, further data are required on the decay of arc temperature and gas electrical conductivity. Experiments are proceeding and measurements are being obtained of these properties.

It is likely that, even at high currents and with, for example, air blasts, the same recovery phenomena and régimes will exist, but it is to be expected that the recovery period will be very much shorter. Experiments under these conditions are planned. The result may indicate the conditions which produce the extremely rapid recoveries encountered in practical circuit-breakers.

(6) ACKNOWLEDGMENTS

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THE APPLICATION OF LOW-PRESSURE RESINS TO SOME HIGH-VOLTAGE SWITCHGEAR DESIGNS

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SUMMARY

The paper outlines the properties of the epoxy and polyester resins which were chosen for application to high-voltage switchgear. Manufacturing methods for casting and impregnating with these resins and for reinforcing them are outlined, and the problems which have arisen and the steps taken to overcome them are described. Examples are given of the ways in which the resins may be applied to various high-voltage switchgear designs, and an indication is given of the advantages so obtained.

(1) INTRODUCTION

The insulants used in switchgear may be divided into two classes: those associated with arc extinction, and those used for insulating busbars, current and voltage transformers, bushings, driving rods and the like. The paper is concerned with the latter class. Such insulants, in addition to having suitable electrical and mechanical properties, should be non-hygroscopic, flame retarding, and capable of being readily formed into complex shapes. None of the conventional types of insulation such as oil, compound, varnished tape, Bakelized paper, and phenolic mouldings possesses all these properties. As a consequence, they are often used in combination; for example, the primary windings of voltage transformers are usually insulated with varnished tape and oil and the leads taken through porcelain bushings. However, epoxy and polyester resins are available having many of the required qualities. These synthetic resins are transformed into hard infusible materials by the addition of hardeners or catalysts—a process known as 'curing'. No volatile products are produced during curing; thus articles of the required shapes may be moulded at low pressures, and fine-wire coils may be satisfactorily impregnated.

The first record of the use of epoxy and polyester resins for high-voltage equipment dates from 1947, when current and voltage transformers insulated with these materials were marketed in Switzerland. This prompted investigations into the use of these insulants for other switchgear components, and the investigations indicated that the dimensions of switchgear could be reduced, particularly within the 6–15 kV range, by making the insulation for conductors of complicated shapes, including any associated bushings or orifices, as a single moulding. An example of this is the 3-phase busbar unit shown in Fig. 1. Again, it was known that these resins, when reinforced by the inclusion of glass fibres, could withstand very high impact and tensile stresses, and it was therefore considered that they could be used to make circuit-breaker bushings and driving links, with further saving in size and weight.

The main disadvantages of these resins are their large contractions during the curing process, and their high coefficients of thermal expansion. The value of the latter for epoxy resins is approximately three times, and for polyester resins approximately five times, that for copper. Thus, where copper is embedded in resin, considerable stresses may be set up during temperature changes. In this respect epoxy resins are preferred, but they cost almost three times as much as polyester resins, and this restricts their application.

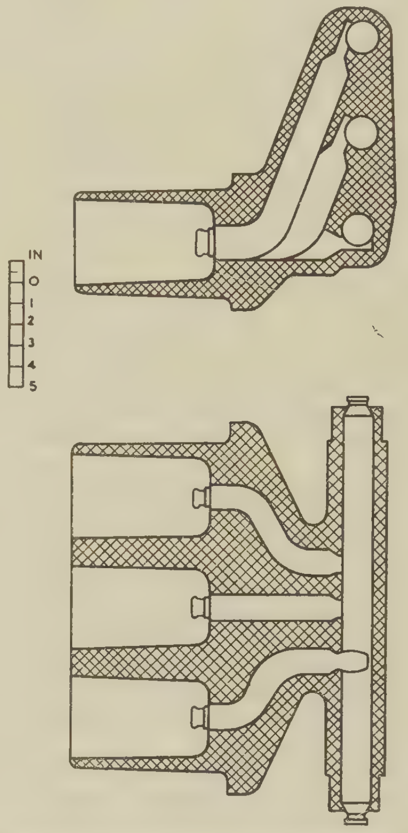


Fig. 1.—Three-phase busbar unit with integral spouts—11 kV rating.

Early experiments carried out by the authors were confined to the casting of epoxy resins to form small bushings and current transformers of simple shapes. The results were encouraging and production commenced on a small scale. Later, when larger and more complex castings were made, fractures occurred. Other difficulties were also encountered; low-ratio current transformers insulated with resin were found to have too small a margin of strength when short-circuit currents were applied; voltage-transformer primary windings were difficult to impregnate, and the early methods used for reinforcing resin with glass fibres resulted in poor electrical properties. Further research was therefore necessary before production could proceed.

(2) CHOICE OF RESIN

There are many types of epoxy and polyester resins having widely differing characteristics.[1,2] The properties of those

The authors are with A. Reyrolle and Co., Ltd.

chosen for casting and impregnating, and for reinforcement with glass fibres, are given.

(2.1) Epoxy Resins

Epoxy resins are usually made from diphenylol propane and epichlorhydrin, and are cured by adding a fairly large proportion of hardener. Those described as Araldite B and Araldite F were used because of their high plastic-yield temperature and good insulating properties.

Araldite B, before the hardener is added, is solid at room temperature and liquefies at 120° C. The most suitable hardener is phthalic anhydride, which when added to the liquid resin causes it to harden in one to two hours, and completely cure in 14 hours. The chemical reaction between an epoxy resin and its hardener is exothermic, and since resins are poor thermal conductors this may cause cracking when the material is used in bulk. Of the resins available, the combination of Araldite B and phthalic anhydride produces the least exothermic reaction and has the smallest coefficient of expansion, and for these reasons it was chosen for casting. Its rapid hardening makes it unsuitable for use as an impregnant and for reinforcement with glass fibres.

Araldite F is a viscous liquid at room temperature and will remain in this state for several months, even when an anhydride hardener is added. If the temperature is raised to 120° C and an accelerator is added, curing occurs in a few hours. This material therefore lends itself very readily to reinforcing processes, and indeed, when used with glass fibres, it has probably the best mechanical properties of any known high-voltage insulating material.

(2.2) Polyester Resins

Polyester resins are not very suitable for casting purposes, because their high curing and thermal contractions, almost twice those of epoxy resins, tend to cause fractures. They are, however, very suitable for impregnated and reinforced articles. For these purposes the resins are usually made from a dihydric alcohol, such as ethylene glycol, and an unsaturated acid, such as maleic or fumaric acid, and are liquids. Styrene is added to thin the resins to make them suitable for impregnation, and they are cured by peroxide catalysts.

Bakelite polyester SR.17449, with the addition of 50% by weight of styrene and a very small quantity of peroxide catalyst, was chosen by the authors for their impregnating processes. The 'pot life' of this mixture, i.e. its useful life after the catalyst has been added, is almost a year at room temperature, and although its viscosity is very low—almost as low as that of switch oil—it will harden very quickly when the temperature is raised to 100° C. It has a high electric strength; values of 240 volts/mil were obtained in tests made in accordance with B.S. 771.

Polyester resins react with copper, causing corrosion. This corrosion is generally limited to a thickness of a few mils, and is therefore usually unimportant where the copper section is large, but it may cause trouble by unduly reducing the cross-section of fine wires. The formulation chosen causes little corrosion.

Since they are at present cheaper than epoxy resins, polyester resins are often used for reinforcement with glass fibres in preference to Araldite F, when the mechanical requirements are less stringent.

(3) MANUFACTURING TECHNIQUES AND DIFFICULTIES

(3.1) Casting with Epoxy Resins

(3.1.1) Use of Fillers.

The use of a filler such as silica with epoxy casting-resins not only reduces the cost but also improves the electrical properties, notably the resistance to tracking. The thermal coefficient of expansion and the curing contraction are both reduced, which is beneficial for casting (see Section 3.1.3). The mechanical properties are also modified (see Table 1): in particular, the tensile strength is slightly reduced and Young's modulus increased.

The production work described in the paper was done using silica flour to a British Standard 120 mesh. Experimental work has since shown that the mechanical properties may be improved by using a British Standard 300 mesh. In both cases, if too much very fine silica is present, or if the proportion of silica to resin exceeds 2·5 to 1 by weight, the mixture is too viscous to cast. The hardening process is accelerated by the presence of water, and care must therefore be taken to keep the mixture dry to ensure that sufficient time is available for casting (see Fig. 2).

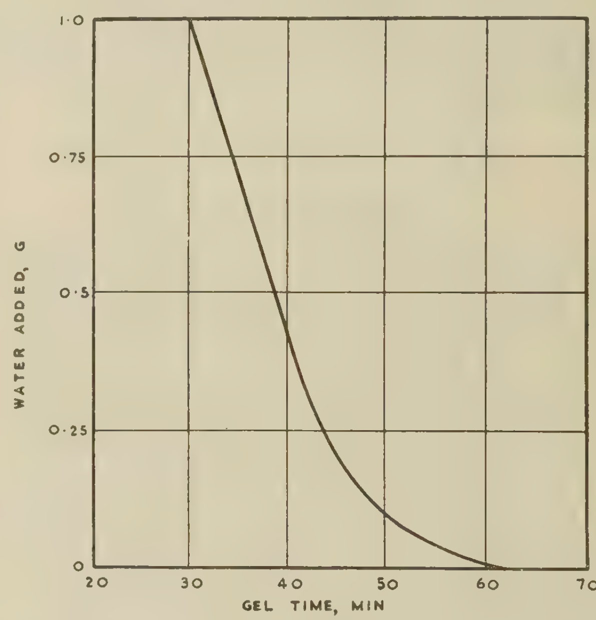


Fig. 2.—Effect on gel time of adding water to epoxy casting resin.
Formulation: 40 g Araldite B.
12 g Phthalic anhydride.

(3.1.2) Prevention of Voids.

To prevent low-pressure bubbles within the castings it is necessary to remove all gas from the mixture, in particular the thin film of air adhering to the silica particles. This can be achieved by casting under vacuum, and there are many variations of this process in use today. In a typical method, the resin and silica are heated and mixed under vacuum, the hardener is then added and stirring under vacuum is continued to remove the air introduced. The mixture is then drawn into moulds inside a tank evacuated to about 1 mm Hg. Once the moulds have been filled, and while the mixture is still fluid, the vacuum is broken and the castings are allowed to cure at a temperature of 120° C. Since the resin commences to gel about one hour after the addition of the hardener, the second stage of vacuum mixing must be short—usually 5–10 min—and therefore large pumps and high vacua are necessary.

(3.1.3) Casting Fractures.

In the early stages of this project, the castings were mainly articles of simple shape, e.g. post insulators and bushings. The copper conductors were treated with silicone grease to allow movement of the resin relative to the conductors during temperature change. For articles with straight conductors this

Table 1

PROPERTIES OF A TYPICAL EPOXY CASTING RESIN

Silica content	Electric strength of ⅛ in plate at 15°C	Power factor at 15°C, 10 kV and 50 c/s	Volume resistivity at 15°C	Permittivity	Surface flashover between 1 in diameter discs		Tracking resistance		Tensile strength	Compressive strength	Cross-breaking strength (B.S. 771)	Impact strength using notched IZOD (B.S. 771)
					6 in in air	3 in in oil	Steam test Micafil	E.R.A. test at 250 V				
Parts per 100 parts of resin	volts/mil		ohm-cm $\times 10^{14}$		kV	kV	sec	sec	lb/in² $\times 10^3$	lb/in² $\times 10^3$	lb/in² $\times 10^3$	ft-lb
Zero	416	0·0024	4·8	4·15	75	105	246	268	9–12·5	15–18	18–19	0·3–0·4
150	510	0·0104	8	4·7	75	105	>7200	>600	8·5–12*	25–29*	12–16*	0·3–0·4
200	500	0·0104	>8	4·7	75	105	>7200	>600	7–12	30–31	10–14	0·3–0·4
250	460	0·0144	>8	4·9	75	105	>7200	>600	7–12	30–35	10–14	0·3–0·4

Silica content	Young's modulus	Specific gravity	Coefficient of linear expansion	Thermal conductivity	Plastic-yield temperature for deflections >2 mm of cantilever 80 mm long by 6 mm²	Moisture absorption for 24 h immersion at 15°C	Oil absorption for 24 h immersion at 15°C
Parts per 100 parts of resin	lb/in² $\times 10^6$		per deg C $\times 10^{-6}$	cal/sec-cm² per deg C/cm $\times 10^{-4}$	deg C	%	%
Zero	0·5	1·22	60–63	4·7	100	0·026	Zero
150	1·3	1·73	35–39	12	115	0·02	0·002
200	1·5	1·84	30–35	15	120	0·02	0·002
250	1·5	1·9	30–33	17	120	0·02	0·002

* The higher values are, in general, obtained when using silica of British Standard 300 mesh in place of the 120 mesh.

treatment was successful, but when large bent conductors were embedded in resin they were unable to move axially and cracking often occurred. The conductors were then covered with three or four layers of cotton tape and this eliminated the trouble. This method was successfully employed for several years in the manufacture of bushings and current transformers. Subsequently, when busbar units comprising three long copper conductors embedded in resin were made (see Fig. 3), cracking sometimes occurred even though the conductors were covered with cotton tape. Such fractures were detected when the article was stripped from the mould whilst still hot, or after two or three days, or even, on rare occasions, after several weeks.

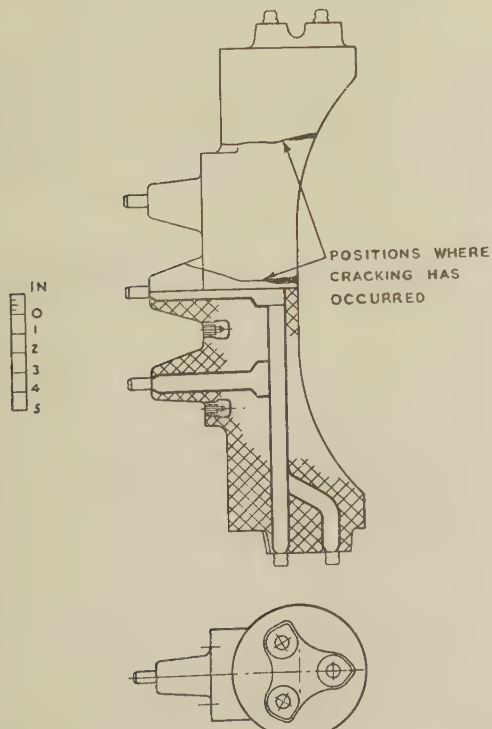


Fig. 3.—Cracking in cast-resin insulated busbar unit.

(3.1.3.1) *Investigations into the Cause and Prevention of Fractures.*

The curing contraction, which takes place at constant temperature, was first investigated using unfilled resin. The apparatus used is described and illustrated in the Appendix. A continuous record was obtained of the contraction during the curing period. Measurements were made at different curing temperatures; the results, together with values of the viscosity of the resin measured during the curing period, are shown in Fig. 4. The results indicate that a large proportion of the

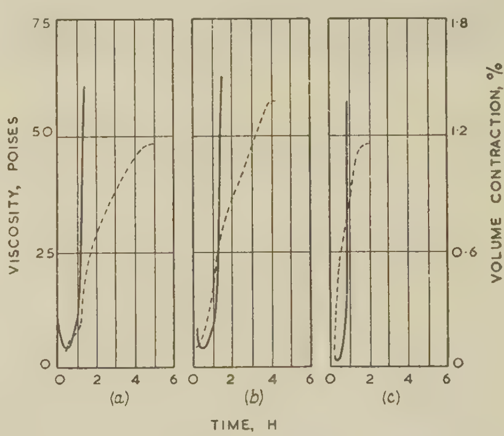


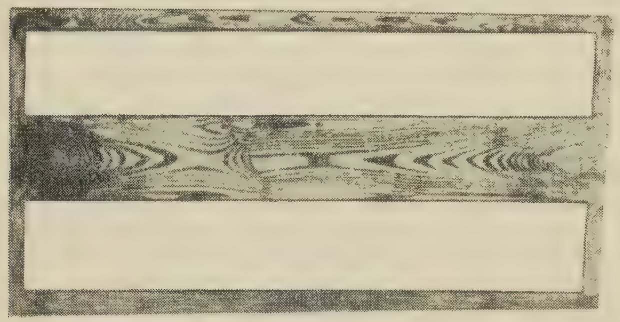
Fig. 4.—Curing characteristics of Araldite B unfilled casting resin.
—— Viscosity.
---- Contraction.
Curing temperature: (a) 120°C.
(b) 130°C.
(c) 140°C.
The total curing contraction is 1·5%.

contraction occurs during the first one and a half hours after the addition of the hardener, and that the resin is solidifying rapidly at this time. They also indicate that the curing temperature does not greatly affect the total amount of the contraction, but that it has a marked effect on the rate of contraction.

The patterns of the strains set up by the curing contraction and the thermal contraction during subsequent cooling were next examined.

Small blocks of unfilled resin were cast containing straight bars of (i) the solid unfilled resin and (ii) copper. These bars were of square cross-section and were de-greased: the moulds were polished and coated with a silicone release-agent. Unfilled resin was used for casting to accentuate the contraction effects and to allow the strain patterns to be photographed by polarized light.

Fig. 5 shows the results obtained—areas of high strain are indicated by crowded lines. In the samples containing two parallel resin bars spaced ½ in apart, cracking did not occur, but the strain concentration—due almost entirely to the curing contraction—was very great, particularly near the ends of the



(a)

(b)

Fig. 5.—Stress distribution patterns in resin castings.

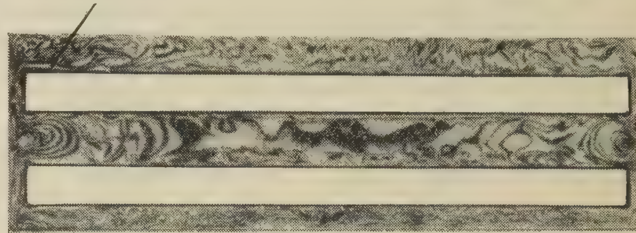
(a) Copper bars embedded.
(b) Resin bars embedded.
All bars are 6 in long and of ½ in square cross-section.

bars. In the samples containing two copper bars spaced ½ in apart, the additional strains due to the different thermal contractions of the resin and the copper caused fracture during cooling. When two copper bars were placed parallel and touching, i.e. as though they were one bar, the strains were much reduced and cracking did not occur. All these experiments were done at 130° C. When further experiments were performed with spaced copper bars at 140° C, the strains were more severe, fractures often occurring at the end of the curing period. This effect occurs while the resin is passing through the gel state, in which it is easily torn. At 140° C the rate of contraction is raised and this seems to increase the chances of tearing.

The fracture of the sample with the two copper bars spaced apart can be explained by considering the resin between the bars as consisting of a large number of thin laminae at right angles to the length of the bars. If the edges of these laminae adhere to both bars while curing takes place, they will be bowed and lengthened, and high strains will be set up. In the case where, in effect, there is a single bar, the resin laminae may adhere to the bar but not to the mould; they will then bend and shorten, and thus the resin will be strained locally near the bar, but the stress will be considerably less than with the spaced bars.

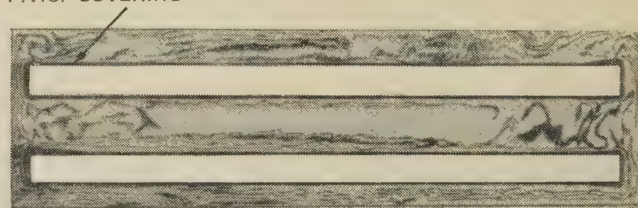
A search was then made for a covering material for the bars which would be soft enough at 130° C to act as a cushion for the contraction of the resin on to the bars, and which would not

P.V.C. COVERING



(a)

P.V.C. COVERING



(b)

Fig. 6.—Stress-distribution patterns in resin castings.

(a) P.V.C. covered copper bars embedded.
(b) P.V.C. covered resin bars embedded.
All bars are 6 in long, and of ½ in square cross-section.

adhere to the resin but allow it to slip along the length of the bars. Polyvinyl chloride has these properties, and samples of resin and copper bars coated with this material were embedded in resin. The strain patterns obtained are shown in Fig. 6, which by comparison with Fig. 5 shows that the strains were very much reduced by the p.v.c. covering. Fractures did not occur during curing or cooling.

In order to verify these conclusions on full-scale models, a number of busbar units of the type shown in Fig. 3 were cast in unfilled resin and cured at 130° C. The following points were observed:

(a) With bare copper conductors, lateral cracks occurred at random points along and between the bars, irrespective of whether they had been greased or de-greased.

(b) When the copper bars were covered with three layers of cotton tape there was some improvement, but areas of high strain were observed under polarized light and occasional cracks occurred. The benefits obtained from the use of cotton tape can be attributed to the fact that the outer layers of the tape move in an axial direction when the resin contracts during the curing stage. The amount of movement permitted depends upon several factors, e.g. the winding tension and the quality of the tape. The movement of the tape, however, was not always sufficient to prevent excessive strains, particularly where long parallel bars were embedded in resin.

(c) The shape of the busbar casting was altered and straight conductors were used, covered with cotton tape as in (b). The results were the same as in (b), indicating that the shapes of the busbar conductors were not particularly important.

(d) Conductors covered with 0·04 in p.v.c. tape gave excellent results—the castings remained sound, even after being subjected to temperature changes of +100° C to −60° C. The strains were much

less than in any of the previous examples. Even when busbar units made with unfilled resin were cured at 140° C (which, as indicated in Fig. 4, causes a greater rate of curing contraction than curing at 130° C, in addition to the increased thermal contraction), they remained sound.

The full-scale experiments thus confirmed the results of the investigation made with the small sample bars. As a result, it was decided that wherever possible solid metal parts embedded in resin should first be covered with a layer of p.v.c. Any new designs would be checked by making prototypes using unfilled resin and examining them under polarized light.

(3.2) Impregnating with Epoxy and Polyester Resins

The problem of impregnating the multi-turn fine-wire primary winding of a voltage transformer with resin and insulating it from the core and secondary winding can be solved in several ways.

In one method, the primary winding has paper inter-layer insulation, and is placed in a mould and packed in position with silica powder. Thereafter, the winding and the powder can be impregnated with an epoxy resin, such as Araldite F, under vacuum at 80° C, and later cured at 100° C. The advantage of this method is that impregnation and insulation of the winding are performed in one operation. The disadvantages lie in the difficulty of holding the winding in place and ensuring that all spaces outside the winding are filled with silica, and of ensuring complete removal of moisture from the inter-layer insulation because of the blanketing effect of the silica.

Another method employed in the United States avoids the liquid impregnation stage by using a different type of polyester resin in film form, e.g. that known as Melinex, for the inter-layer insulation. The winding is placed within the mould inside a tank which is heated to 130° C and then evacuated. Casting is done in the usual way. The polyester film is elastic at the casting temperature, and when the vacuum is released the occluded gas bubbles collapse and the winding contracts slightly. The disadvantage of this method is the very high cost of the polyester film. Although this film has a high puncture strength, it is not possible to take advantage of this fact to reduce the thickness of the inter-layer insulation below that required for resin-impregnated paper, because the gas bubbles are not completely removed from the winding, and this type is prone to deterioration under the action of corona; the inter-layer thickness must therefore be sufficient to prevent corona at the working voltage.

In a method which has given good results, the winding is vacuum impregnated with a catalysed polyester resin and then transferred to a hot oven, where the resin in the winding rapidly cures. The remaining resin in the impregnating tank is not heated and thus its pot life is not shortened. The impregnated high-voltage winding is cast in resin, as described in Section 3.1, and then assembled together with the core and secondary. Polyester resin is used because it is cheaper than epoxy resin and has a longer pot life. To prevent any corrosion of the fine copper wire by the polyester resin, enamel-covered wire is used.

This method has the advantage that primary windings can be impregnated and cured in batches and it is therefore suitable for quantity production.

(3.3) Reinforcement of Epoxy and Polyester Resins

For applications where great strength and low weight are required, e.g. circuit-breaker driving-rods, the resin must be reinforced. The essence of reinforcing lies in the efficient transfer of stress from the resin to the reinforcing medium. Glass fibres are used because of their high modulus of elasticity, high tensile strength and durability.

It has been found[3] that the best electrical and mechanical properties are obtained with borosilicate glass of low alkali content, known as 'E' (or electrical) glass. The epoxy resins adhere more strongly than the polyesters to the glass, but the adhesion of both is improved by suitable treatment of the glass surface.

Even with treated borosilicate glass, however, poor electrical properties may be obtained. For example, a 4 in diameter tube of epoxy resin reinforced with glass fibres, when tested under oil, flashed along the surface between electrodes 9 in apart at 24 kV. It was suspected that moisture was present on the surface of the glass fibres, and therefore a similar tube was made using glass that had been heated by infra-red rays immediately before applying the resin. This tube, when tested under the same conditions, withstood 65 kV, which was the maximum voltage that could be applied with the particular test arrangement. The mechanical strength under wet-test conditions was also improved by this treatment: specimens which were immersed in boiling water for 2 hours and then dried had tensile strengths of 95% of the values obtained prior to immersion.

(3.4) Criteria of Electrical Performance

Power-factor/voltage tests were at first adopted as a method of checking the quality of resin-insulated articles. It was found, however, that the readings obtained varied over a wide range, owing to the varying surface conditions of the resin arising from the use of a silicone release agent in the mould and the varying humidity conditions. The method was therefore unsuitable, and discharge tests were substituted.

The policy adopted was that, when the articles were tested with a discharge bridge at a voltage 15% higher than the working voltage, the discharge should not exceed 200 pC. This value was adopted as an interim measure until more information was obtained about the effect of internal discharges on the life of epoxy resins.

During the past three years a large number of components, including current transformers, have been undergoing duration tests at voltages at which internal discharges occur, and at a supply frequency of 50 c/s. The magnitudes of these discharges are in excess of 200 pC, and at present there is no evidence of any deterioration.

Further work has been done on this subject by other investigators,[4] and by the authors, using test methods based on work done at the E.R.A.[5,6] The test equipment used is designed to apply voltages up to 10 kV at frequencies ranging from 1 to 10 kc/s to samples of insulation; the reason for increasing the frequency is to reduce the time of breakdown of the insulation due to corona discharge. The evidence which has so far been obtained indicates that epoxy resins are superior to synthetic-resin-bonded paper, and that, subjected to internal discharges at stress levels of approximately 40 volts/mil, they have a very long life. This value has therefore been adopted as a design parameter.

(4) DESIGN AND APPLICATION

In general, low-pressure resins cannot at present be applied economically to switchgear rated at voltages above 15 kV, because the problem of providing voltage-stress control in resin bushings has not yet been satisfactorily solved. In voltage transformers, however, the primary winding can be designed to give a measure of stress control, and here it has been possible to apply resin up to 33 kV. The special design features associated with resin-insulated current and voltage transformers, busbars and connectors, and the ways in which these components are used in some typical 6·6 and 11 kV switchgear units, are described below.

(4.1) Current Transformers

Resin-insulated current transformers have been made in many forms, but, for a wound-primary current transformer, that shown in Fig. 7 is attractive because it permits the use of high-permeability wound-strip cores which, together with the primary and secondary windings, can be hermetically sealed by the resin.

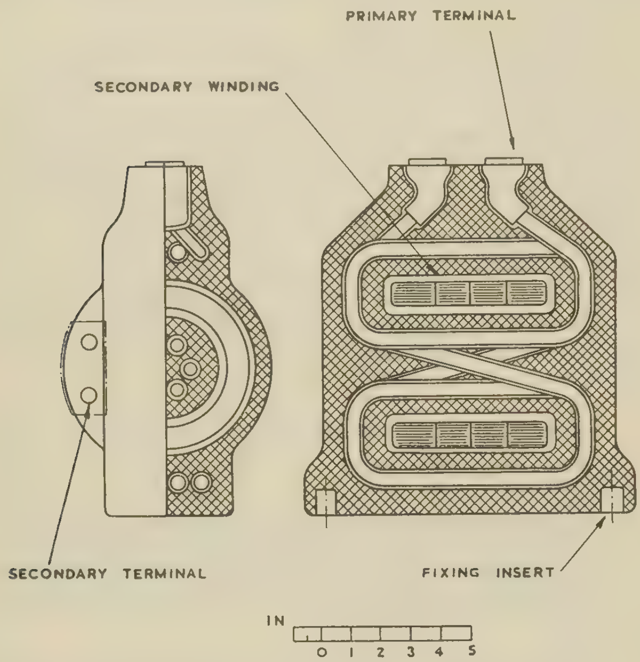


Fig. 7.—Cast-resin-insulated wound-primary current transformer.

During the casting process, the primary winding must be accurately located within the core and secondary winding. This may be done by providing resin spacers, or by first casting a coat of resin on the core and secondary, then winding the primary and finally casting the outer coat of insulation. Both methods have proved satisfactory, but more accurate dimensional control is possible with the latter.

Table 2 gives the results of tests which were done on 11 kV wound-primary current transformers of the kind shown in Fig. 7. These show that power arcs over the surface of, or through, the epoxy-resin insulation are not liable to cause fires. When a flashover occurred over the surface of the insulation, the transformer was serviceable immediately it was cleaned. Immersion in water did not damage the insulation.

It was found that the insulation of some low-ratio wound-primary current transformers fractured during repeated short-time current tests. The cross-section of the primary winding was designed to limit the temperature rise to 200° C at the end of the rated period. The fractures occurred when the tests were repeated with short rest periods between them. The reason for this was that the copper had not cooled sufficiently at the start of the repeat tests—the final temperature at the end of the tests approached 300° C, and the expansion of the primary loops, which were rigidly held by the resin, exerted sufficient force to fracture the resin. Although these transformers complied strictly with B.S. 81, the margin was not considered adequate. Improved performance was obtained by covering the primary conductors with an elastic material which allowed them to move sufficiently to prevent cracking of the resin. Table 3 compares the test results obtained with transformers having windings with and without elastic coverings. The problem does not arise with bar-primary transformers, first because the primary cross-section is usually so large that the temperature rise produced by short-circuit currents is relatively low, and secondly because the primary conductor is straight and thus can easily be arranged to slide inside the resin.

(4.2) Voltage Transformers

The layer type of primary winding has been adopted for the voltage transformers shown in Fig. 8. (The layer-to-layer capacitances are large in relation to the layer-to-earth capacitances, and this form of winding can therefore be made to have a high impulse strength.) Such a construction would not be satisfactory if phenolic resins were used, because of the difficulty during curing of driving out the solvents through the fine wires. This problem does not arise if polyester or epoxy resins are used. The resin also provides solid insulation at the ends of the layers, which adds to the impulse strength of the windings. Typical test results for transformers impregnated with polyester resin by the third method described in Section 3.2 are given in Table 4. The windings of these transformers are not smaller than the orthodox ones insulated with oil-impregnated paper; indeed they tend to be larger, because the maximum permissible inter-layer stress is lower, the value chosen being 55 kV/cm under the induced-voltage test conditions. This corresponds to 45 volts/mil at the working voltage.

The overall dimensions of the resin-insulated 11 kV transformers are nevertheless much less than those of the normal oil-filled transformers, because the oil, its containing tank and

Table 2

Arcing Tests Applied to 11 kV Cast-Resin-Insulated Wound-Primary Current Transformers

Test condition	Applied test	Result
No. 38 s.w.g. copper wire connected between primary and earth, and in contact with the insulation.	Primary winding connected to 11 kV source. A power arc of 18 kA r.m.s. was sustained for 15 cycles.	A thin layer of carbon found on the surface. No fire or damage. Removal of carbon restored the transformer to serviceable condition.
A breakdown between primary and secondary was caused by applying a high-voltage low-current source to the transformer when immersed in oil. The transformer was then mounted in air in a sheet-metal chamber.	The primary winding was connected to an 11 kV source. A power arc of 13 kA r.m.s. was sustained for 15 cycles.	Two pieces of resin were blown off the transformer. There was a quantity of black smoke, but no fire.
A transformer was immersed in water for 24 hours and then withdrawn, and a power-frequency voltage applied to the primary.	36 kV at 50 c/s was applied for 1 min. The transformer was dried and the test repeated.	Intense corona but no flashover. No corona. Transformer satisfactory.

Table 3

EFFECT OF REPEATED SHORT-TIME CURRENT TESTS ON 40/5 AMP CAST-RESIN-INSULATED CURRENT TRANSFORMERS WITH AND WITHOUT CUSHION ON PRIMARY

Test current	Duration of current	Subsequent rest period	Estimated time for test current to produce 200° C rise in primary	Visible effect of test current	
				Transformer without cushion on primary	Transformer with cushion on primary
kA	sec	min	sec		
7·85	3·13	105	4·1	Nil	Nil
7·85	3·09	30	4·1	Nil	Nil
7·85	3·11	1 200	4·1	Nil	Nil
13·8	1·62	30	1·33	Nil	Nil
13·8	1·62	25	1·33	Cracked	Nil
15·3	1·62	30	1·08		Nil
13·5	1·62	10	1·39		Nil
13·8	1·62	10	1·33		Nil
13·6	2·01	10	1·37		Nil
13·6	1·98	Zero	1·37		No cracking; smoke emitted from primary terminals

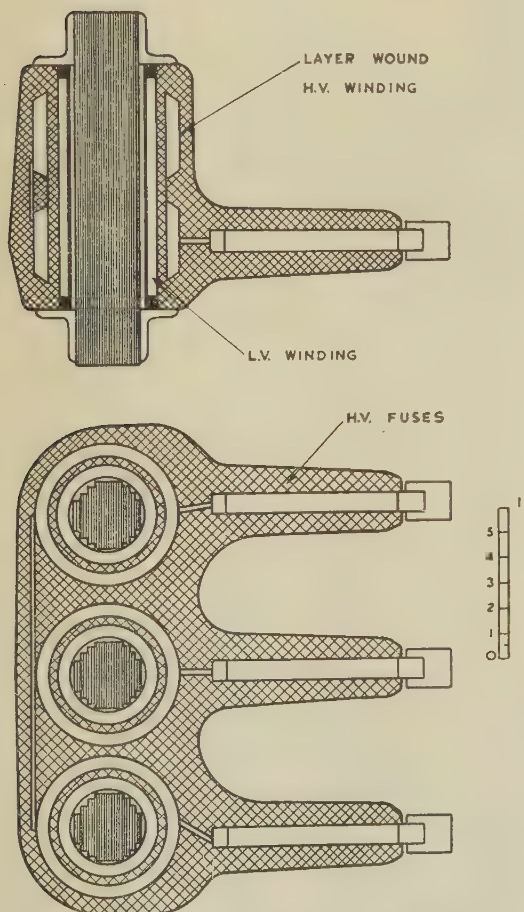


Fig. 8.—Cast-resin-insulated voltage transformer, 11 kV 3-phase.

bushing insulators are not required, and because the high-voltage fuses can be located within the resin.

Melinex polyester film (cf. Section 3.2) has been used for the inter-layer insulation in an experimental single-phase 11 000/110 volt transformer manufactured in Great Britain. This had the same relevant external dimensions as those shown

Table 4

TYPICAL TEST RESULTS WITH 11 kV AND 33 kV CAST-RESIN-INSULATED VOLTAGE TRANSFORMERS

Test	Results	
	11 kV transformer	33 kV transformer
50 c/s voltage applied between h.v. winding and earth	Breakdown occurred at 60 kV	
Induced voltage test at 300 c/s	H.V. winding failed between turns at 70 kV	
Impulse voltage test with 1/50 μs wave, transformer in air	Withstood 106 kV peak	Withstood 200 kV peak
Impulse voltage test with 1/50 μs wave, transformer in oil	H.V. winding failed at 203 kV peak	H.V. winding failed at 575 kV peak

in Fig. 8 and withstood the application of very high impulse voltages, breakdown occurring at 330 kV.

(4.3) Switchgear Arrangements

Some examples of the use of low-pressure resins in high-voltage switchgear are shown in Figs. 9, 10 and 11.

(4.3.1) Outdoor Oil-Break Switchgear.

Fig. 9 shows an arrangement of oil-break switchgear, rated at 200 amp 11 kV 150 MVA, for use in outdoor substations. Wide variations of temperature and humidity are common in such situations, and it is therefore advisable to eliminate all creepage surfaces exposed to air. This has been achieved in this design by making the current transformers and the busbars (see Fig. 3) as 3-phase cast-resin-insulated units, and in both cases forming the insulation of the terminals as an integral part of the unit. In comparison with orthodox compound-filled busbar and current-transformer chambers, this design has reduced the overall height of the equipment by 10%, increased the insulation security and reduced the cost.

Further savings in height have been achieved by embedding

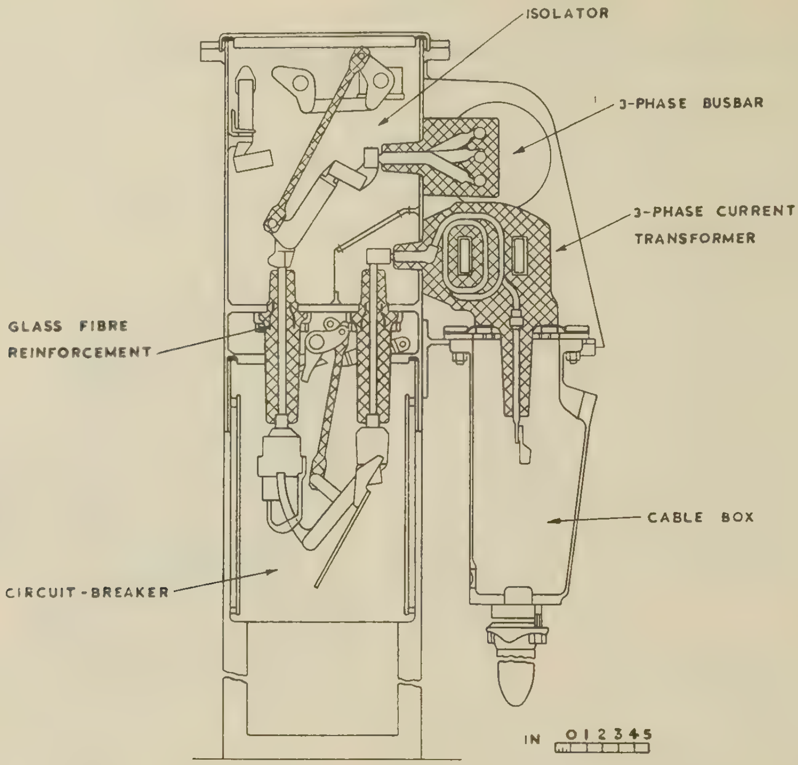


Fig. 9.—Outdoor oil-break switchgear unit, 200 amp 11 kV 150 MVA, showing resin parts.

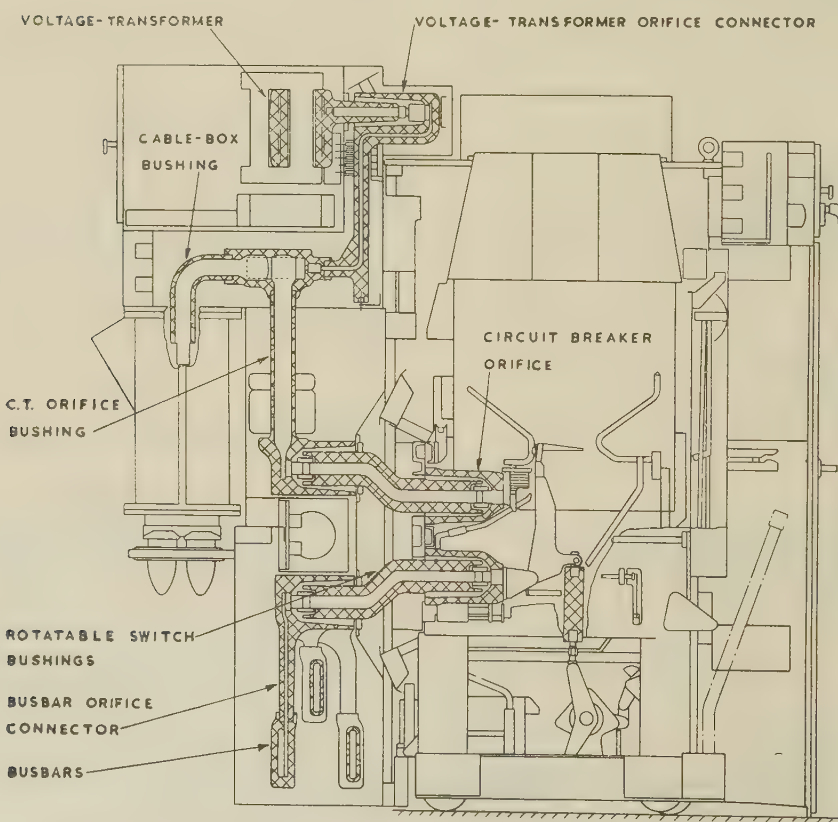


Fig. 10.—Indoor air-break switchgear unit, 1 600 amp 11 kV 500 MVA, showing resin parts.

ıe circuit-breaker contact-fixing blocks within the ends of the ircuit-breaker bushings, and by casting these bushings with ıtegral mounting flanges. These bushings must be capable of vithstanding severe lateral shock forces when short-circuits occur, nd therefore a glass-reinforced-resin moulding is embedded in he flange of each of them.

The operating links of the circuit-breaker and the isolator are nade of glass-fibre-reinforced resin. When these rods were ompared with s.r.b.p. rods, it was shown that they could withtand more than twice the load although the weight of material vas nearly halved. The breaking load, for the glass-fibre-einforced resin links was 4 tons with a weight of 135 g, whereas, or the s.r.b.p. links, it was only 1·6 tons with a weight of 223 g.

(4.3.2) **Indoor Air-Break Switchgear.**

Fig. 10 shows an indoor air-break circuit-breaker panel rated at 1 600 amp 11 kV 500 MVA. Resin is used extensively for insulating bent connectors and their associated terminals, in order to save space. Where an orifice insulator is required for a terminal, it is cast integrally with the insulation of the connector. A notable feature of the panel is the use of resin-insulated rotatable cranked bushings on the circuit-breaker. By rotating these through 180° from their service position, either the cable or the busbars may be earthed through the circuit-breaker.

Air creepage paths cannot be eliminated to the same degree in air-break as in oil-break circuit-breakers, because the contacts and ancillary connections are necessarily in air. Nevertheless, it is considered worth while to eliminate as many weak points as possible, particularly on the fixed portion of the panel, where maintenance is infrequent. This has been achieved by covering joints between connectors with resin after assembly.

The roof barriers of the box-like arc-chute are made of polyester resin reinforced by glass fibres.

(4.3.3) **Flameproof Switchgear.**

Fig. 11 shows an arrangement of a flameproof circuit-breaker panel, rated at 400 amp 6·6 kV 75 MVA. Cast resin is used for insulating the conductors and current transformers in the fixed part of the panel.

In order to avoid exposing live busbar or cable connections to explosive atmospheres when the circuit-breaker is withdrawn, isolating connectors are interposed between the circuit-breaker and the terminals in the fixed portion of the panel. These isolators, comprising six high-voltage and twelve low-voltage connectors, are cast in a single block of resin, and the circular flanges of this block are machined to close limits to ensure a flameproof path where it fits in the cylindrical metal casing.

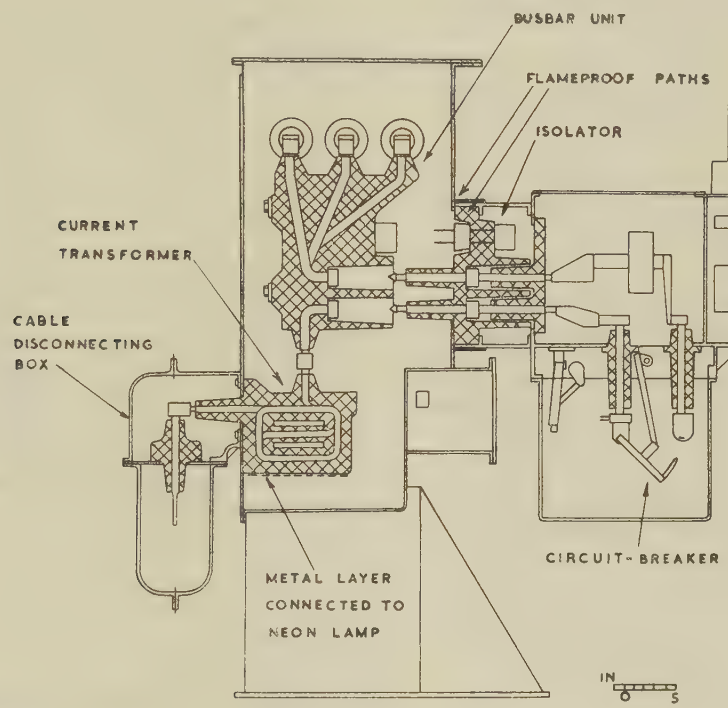


Fig. 11.—Indoor oil-break flameproof switchgear unit, 400 amp 6·6 kV 75 MVA, showing resin parts.

The co-operating plug contacts on the circuit-breaker are also cast in a single block of resin.

It will be evident from Fig. 11 that, while the complicated arrangement of conductors in the fixed portion of the panel can be readily insulated with resin, this would be difficult to achieve with other materials in the limited space available.

In this kind of switchgear, it is important that the busbar joints shall be readily accessible to enable alterations and extensions to be made safely and quickly, and therefore it is usual for the busbars to be lightly insulated with a plastic material which is easily stripped off when alterations are required. Very large creepage surfaces are therefore essential between busbars, and these are easily obtained by suitably shaping the resin insulation.

The isolator is shown in the first withdrawal position, the circuits within the main flameproof enclosure being broken. In the next stage the switch is detached from the isolator and further withdrawn to obtain visible isolation. Live-line indication is provided for each phase by spraying a metal layer on the outside surface of the wound-primary current transformer, and connecting this layer to earth via a neon lamp.

(5) FUTURE DEVELOPMENTS

A considerable amount of work has been done on moulding filled polyester resins, particularly in the United States. Quite recently, a material has been marketed in Great Britain which promises to be suitable for voltages up to 15 kV. This material is obtained from the makers as a dough-like mixture of polyester resin, chopped glass fibres and a mineral filler. This is moulded under heat and pressure, the moulding cycle being approximately 10 min, and is therefore very suitable for compression moulding where quantity production is required. The material has good electrical properties, and it has an impact strength about ten times that of cast epoxy resin, with almost the same tensile strength. Difficulties are being experienced at present in moulding thick sections, but when these are overcome this material should show appreciable saving in cost in comparison with cast resin, and have a wide application for articles which can be suitably designed for compression moulding.

At 6·6 and 11 kV, reinforced-resin circuit-breaker tanks with integral cast-resin bushings have already been made, and when this technique is fully developed it is expected that there will be a considerable saving in space.

The application of low-pressure resins to switchgear for 33 kV and above cannot be profitably explored until the problem of stress control of cast-resin bushings (particularly bent ones) has been thoroughly mastered. Various alternatives are being examined.[7]

There is little experience of these resins mounted in exposed outdoor situations where the surface of the resin is subjected to electric stress, but laboratory tests show that, whilst they have good anti-tracking properties, epoxy resins are inferior to porcelain for outdoor use. Tests on samples have shown that brush discharge, humidity and ultra-violet light have a detrimental effect. In particular, ultra-violet light causes crazing of the surface in which particles of dirt and moisture lodge, and this accelerates breakdown by tracking. These results were obtained on samples having only a small proportion of filler in the resin, and it has been shown that these deleterious effects can be minimized by increasing the proportion of filler. Even so, there is little doubt that the present epoxy resins are unsuitable for use as insulators in unshaded outdoor situations, and a search is being made for alternative resins and surface coatings.

(6) ACKNOWLEDGMENTS

The authors wish to thank the Directors of A. Reyrolle and Co. Ltd., for permission to publish the paper, and their colleagues for help in preparing it. They are also indebted to Moser Glaser, Switzerland, the Bushing Co. Ltd., and the I.T.E. Circuit-Breaker Co., Philadelphia, for providing information.

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(8) APPENDIX

Measurement of the Curing Contraction

The arrangement of the apparatus used for recording the curing contraction is shown in Fig. 12. A steel tank containing mercury is immersed in an oil bath heated by a bunsen burner.

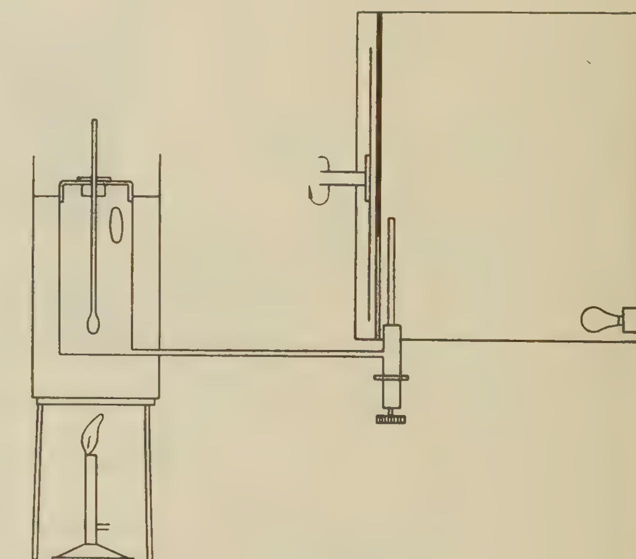


Fig. 12.—Apparatus for recording curing contraction.

The steel tank is connected to a glass tube situated inside a 'dark box'. This tube is painted black except for a narrow vertical strip, back and front, through which the level of the mercury may be observed. Behind the tube is a clock-driven disc to which a sheet of light-sensitive paper is attached. The paper is masked except for a $\frac{1}{16}$in slot in line with the tube. The light source is a 25-watt bulb placed 12 in from the disc, and the clock speed is $\frac{1}{8}$ r.p.h.

The sample of resin and hardener is poured into a small rubber bag, which is then sealed, care being taken to ensure that air is not trapped. The bag is then placed in the mercury and held beneath the surface, the mercury is adjusted to a suitable level in the tube, and the clock started. The temperature of the mercury surrounding the sample is kept at the chosen curing value, and as the resin contracts, the level of the mercury in the tube drops and is recorded on the paper disc.

DISCUSSION ON THE ABOVE PAPER

Before the INSTITUTION, 26*th November, the* NORTH-MIDLAND CENTRE, *at* LEEDS, 3*rd November, and the* NORTH-EASTERN CENTRE, *at* NEWCASTLE UPON TYNE, 23*rd November*, 1959

Mr. C. J. O. Garrard: The production of a new material such as these casting resins is always a challenge to the engineer. It gives him the opportunity for new developments, and for improving in design and cost existing equipments.

There is a tendency abroad to extend the use of all-insulated construction from the medium-voltage range, in which it has, of course, long been in use both here and on the Continent, into the higher-voltage range of 10–30 kV. It is a means whereby material as well as space may be saved and costs cut. The authors are to be congratulated on adapting this tendency to British switchgear practice.

The greatest trouble in the use of casting resins is cracking. As a remedy the authors rely on a p.v.c. coating on the conductors. However, the softening temperature of p.v.c., which is of the order of 120–130° C, may impose a certain limitation on the permissible heating of the conductors by short-circuit currents, or may lead to trouble if the conductors become heated to over 130° C as a result of over-current. We have been concerned also with the possibility of chemical attack on the resin by the p.v.c. after prolonged operation at elevated temperatures.

There are some alternatives to a resilient coating. To deal with radial expansion the resin may be made slightly flexible by certain additions. Possibly the best way to deal with longitudinal expansion is to design the parts so that relative movement of the metal and resin does no harm and to anchor each metal part in the casting at one point only so that free relative movement is possible.

The internal discharge limit of 200 pC at 15% over-voltage seems a little high. We prefer to design for about 1 pC at the service voltage, and find that, if we do this, discharges do not exceed about 10 pC at 15% over-voltage. What is the effect of internal discharges on the p.v.c. coating?

A very important matter, which in the paper is perhaps not given its due weight, is tracking, especially on oil-immersed insulation exposed to carbon deposition. We developed some years ago a method of evaluating insulating materials from this point of view. We found that carbon deposition from previously carbonized oil did not produce the same harmful effects as did the deposit from an arc in the oil in which the test object was placed. The articles under test, therefore, are put under voltage in a bath of oil, and at the same time carbon is produced in the oil by means of a contactor underneath its surface.

On this test ordinary good-quality synthetic-resin-bonded paper breaks down under the standard test conditions in about 130 hours. Synthetic-resin-impregnated wood without any protective coating may last 20 hours, but if it is suitably varnished its life may be 300 or 400 hours. Epoxy resins similar to those used by the authors last from 500 to 1 500 hours, depending on the filler, and epoxy-bonded glass fibre from 500 to 900 hours, depending on the class of resin and on the type of glass.

One discovery we made about fillers is that purity is of great importance; the slightest trace of metallic oxide in the silica is extremely deleterious.

The authors have been very courageous in applying these resins in such large quantity to such a large variety of apparatus, in eliminating earthed enclosures and in doing without the interposition of earthed metal in the tracking surfaces between conductors.

They mention in Section 4.3.2 that they cover joints with resin. How is this done?

We have succeeded in applying stress control to 33 kV epoxy-resin orifice spouts by covering the outside of the top of the spout with a layer of colloidal silver. Where we might otherwise have a stress concentration at the end of the coating, there is a projection on the casting which provides a rounded edge. In bushings we have provided stress control by a helix of copper wire forming a condenser layer.

One point which the authors did not mention is that casting in resin may be used on occasion merely to obtain greater mechanical strength. An example is the series over-current trip coils in direct-operated circuit-breakers. If such coils are cast solid in resin there is a very considerable increase in their strength and resistance to electromagnetic forces.

Mr. N. Care: Considerable emphasis has been given to the relief of mechanical stresses in the curing process. In the development of current transformers we have found that these difficulties are overcome by wrapping the core with foamed-rubber tape with the secondary wound over it. By this method the mechanical stresses have been overcome and the secondary winding has provided an electrical screen. Do the authors see any objection to the use of foamed rubber, provided that a metallized coating is provided between the foamed rubber and the epoxy resin? We have tested such current transformers at 135 000 AT. What m.m.f.'s apply to the tests of Table 3?

We have followed the same treatment with the insulation of copper for 6·5 kA generator connections and no difficulties have arisen with cracking, either during manufacture or in service.

The authors consider that the limit of epoxy-resin-insulated items is 15 kV. Is this limit correct, in view of the fact that on the continent epoxy-resin bushings are used at a much higher voltage without any electrical stress relief?

We have developed a process for the extrusion of Araldite on to copper bars. Could such a method be used for providing electrical stress relief by the adoption of progressive extrusions adding the electrical stress relief layer after each extrusion process?

We have also made considerable use of epoxy resins for spout insulation. We have used epoxy resins, however, because we, unlike the authors, feel that electrical stress can be more easily relieved by the simple addition of a cone in the inside of the spout in contact with the live metal. We can thus achieve a spout insulation which is superior to porcelain. The electrical stresses at the top of the spout can be catered for and, in addition, it is possible to achieve tolerances which are impossible with porcelain, and the design limits are so much better controlled.

Mr. D. M. Cherry: Experience with the many new mixtures of synthetic resins that are being offered demands a cautious approach, and the authors are under no illusions as to the difficulties involved. Epoxy resin has great advantages up to 15 kV, but we would do well to await experiences with it on a large production scale, rather than give it a bad name by premature use at higher voltages, where the problems of stress control and greater thicknesses have yet to be overcome. A weatherproof surface for use out-of-doors would greatly extend its value at higher voltages.

The resins used are complex mixtures and small variations of composition and processing can have a profound effect on the end-product. It is hardly for the user to delve into manufacturing processes, but it is essential to him to have complete and reliable means of testing the product. For an electrical test, discharge measurement is probably the best, but I should like to hear better justification for the proposed discharge limit

of 200 pC. In my view there should be no measurable discharge at the highest working voltage. Could the authors describe the process of degradation under discharge, and give some information as to the speed of the process when there is appreciable internal discharge?

Mr. W. J. Brown: In my experience polyester resin is a most unrewarding material, and I wonder whether some of the problems which the authors have found in their development of voltage transformers and the great difficulties which they have found in 'dough' moulding are caused through using polyester resins.

Epoxy resins are the most exciting insulating materials which the electrical engineer has found since the introduction of the phenolic resins many years ago. It may be an overstatement to claim that the shape and design of h.v. switchgear is determined largely by the insulation which the designer uses. Until now, using the best material available—phenolic-resin-bonded laminated paper—only tubular straight cylindrical shapes have been available to the switchgear designer. Bushings can now be made bent, and they can be bent in three planes if so desired. Insulators, busbars, bushings and post insulators can be embodied in one casting, the casting in itself containing its own means of support.

Mr. H. Davies: In their assessment of the properties of epoxy resins the authors did not give enough prominence to the fact that filled epoxy resins are non-fibrous materials with low water absorption and consequently are particularly suitable for use as insulation under adverse atmospheric conditions indoors. The authors are at the moment against the use of epoxy resins out-of-doors and the weight of evidence supports this opinion. On the other hand, some Continental experience encourages a more optimistic view.

As the authors point out, most of the shrinkage occurs in the first hour or so after adding the hardener and consequently takes place in the liquid state, resulting only in a drop in level. The remainder takes place in the solid state and during transition, and is, of course, very important. The shrinkage causing stress, however, is less than the total value shown on the curves.

Two of the desirable features of impregnating resins are good bond strength and low shrinkage. Epoxy resins are better in this respect than polyesters, although they do tend to have shorter pot lives. Perhaps the authors could comment further on the use of epoxy resins as impregnants.

The presence of moisture in phthalic anhydride reduces the pot life slightly, possibly owing to the formation of the acid. There should be no moisture in the resin or filler when the hardener is added. Consequently, the curve shown in Fig. 2 seems unrealistic, e.g. a reduction in pot life of from 60 to 30 min requires a moisture content of the hardener of about 10%, which is not likely to be obtained under average storage conditions. Will the authors explain how they arrive at Fig. 2, as it seems to be of academic value only?

Dr. J. H. Mason: The rate of deterioration of insulation by discharges of a given magnitude varies with the applied stress and with the ambient temperature. Thus discharges of 200 pC may sometimes cause more rapid damage to epoxy castings than in the authors' experience. It should be remembered also that the discharge magnitude often varies with time of voltage application.* The test voltage should thus be applied for a specified time before the discharge level is recorded.

Fig. A shows the results of tests to compare the discharge resistance of sheet insulating materials. Results for typical laminates show that epoxy-bonded glass fibre has greater discharge resistance than polyester-bonded glass fibre, and both

* Birks, J. B., and Schulman, J. H.: 'Progress in Dielectrics' (Heywood, 1959), Chapter 1.

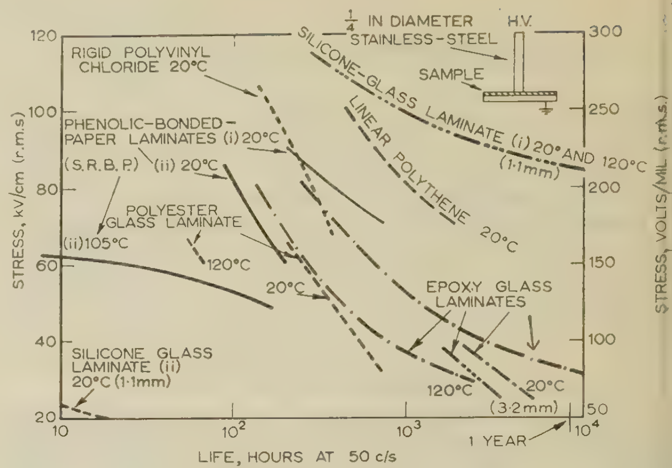


Fig. A.—Effect of stress and temperature on discharge resistance of sheet insulation.

Curves show mean lives of specimens tested in dry air between rod and plane electrodes.
Specimens 1·6 mm thick, except where otherwise indicated.

materials are superior to most phenolic-bonded-paper laminates (s.r.b.p.) particularly at higher temperatures. However at 20° C, some supplies of s.r.b.p. have greater resistance to discharges, as shown by curve (i) of Fig. A. At 20° C, rigid p.v.c. has similar discharge resistance to epoxy-bonded glass laminates, but above 60° C, p.v.c. suffers rapid thermal degradation in the presence of discharges. Discharges of about 100 pC caused 3·2 mm epoxy-bonded glass laminates to fail in about 5 000 hours at 25 kV/cm and 50 c/s.

Table A shows that mechanical strain reduces the discharge resistance of most materials.

Table A

Effect of Mechanical Strain on Discharge Resistance of Glass Laminates at 20° C

Impregnating resin	Thickness	Stress	Life, hours at 50 c/s when samples subjected to a strain of: 0%	0·25%	0·55%
	mm	kV/cm (r.m.s.)			
Silicone ..	1·6	62	>2 600	265	—
Epoxy ..	1·5	62	600 ± 70	500 ± 80	—
	1·5	50	1 100 ± 230	1 200 ± 220	950 ± 160
Polyester	1·75	65	220 ± 20	20 ; 186	—
Melamine	1·6	76	120 ± 10	—	10 ; 17 (T)
	1·6	76	120 ± 10	—	116 (C)

(T) Tensional strain in surface exposed to discharges.
(C) Compressional strain in surface exposed to discharges.

Tables B and C show that epoxy-impregnated-paper bushings suffered permanent damage after an a.c. over-voltage test at $3V_i$, and after impulse flashover tests. Epoxy castings, with silica filler, and porcelain bushings were much less affected.

The E.R.A. has accepted the tracking test recommended by the International Electrotechnical Commission, in place of the rod-and-ring method mentioned in Table 1. Semi-automatic equipment is available to facilitate measurement of the 'comparative tracking index' by the I.E.C. method.*

* Parkman, N.: 'International Tracing Test using Automatic Equipment', *Electrical Review*, 1959, 165, p. 157.

Table B

DISCHARGES OVER 11 kV AIR-TO-AIR BUSHINGS

Bushing material	V_i	V_e after 5 min at $2V_i$	V_i after 5 flashovers	V_e after 15 sec at $3V_i$	V_i 10 min after test at $3V_i$
	kV (peak)	kV (peak)	kV (peak)	kV (peak)	kV (peak)
Epoxy-impregnated paper	11·4	14·8	9·2	7·0	7·8
Epoxy with silica filler (a)	13·7	13·2	13·5	11·5	14·2
Epoxy with silica filler (b)	11·8	11·7	11·2	12·1	12·0
Porcelain post insulators	13·2	12·7	12·5	12·1	12·0

V_i, discharge-inception voltage.
V_e, Discharge-extinction voltage.
Relative humidity, 55%.

Table C

IMPULSE FLASHOVER VOLTAGE FOR 11 kV AIR-TO-AIR BUSHINGS

Bushing material	V_F in successive tests at ½ min intervals			V_F 2 min after previous tests
	kV			kV
Epoxy-impregnated paper	110	100	95	95
Epoxy with silica filler (i)	177	172	125	170
Epoxy with silica filler (ii)	120	115	110	115
Porcelain	65	58	56	58

Relative humidity ~55%.

Mr. K. H. Stark: The authors have used the contraction of a esin when it cures to determine the curing time, whereas my ompany has tended to use the change in electrical and mechnical properties. While the curing times suggested by the resin ippliers are generally correct, they are occasionally in error. his is illustrated in Fig. B, which shows the variation of the

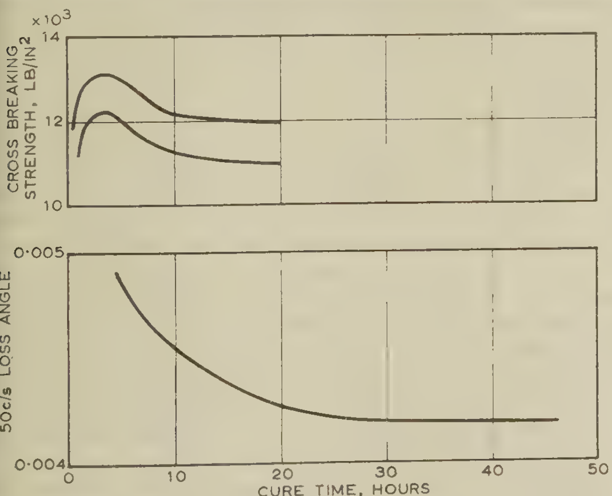


Fig. B.—Variations of 50 c/s loss angle and cross-breaking strength of an epoxy resin at 20° C with curing time.

oss angle and the cross-breaking strength of an epoxy resin ith the curing time. From these curves it will be seen that the uring time is about 20 hours, whereas that recommended by ie suppliers for this particular resin is only 2 hours. It is ssential that a cast resin component should be fully cured before aving the factory, or mechanical stresses may be set up in ervice sufficient to crack the resin. Control of the mechanical stresses within a resin is the key to producing satisfactory cast components for use at high voltages. This can be done in the first place by suitable design, by choosing simple and symmetrical shapes and not embedding in the resin any large metal component with a sharp edge. If a metal insert is embedded it is advisable to apply to the metal surface a pliable material, as suggested by the authors. There are several materials available in addition to p.v.c. Where the authors had a copper temperature of 300° C, were they using silicone rubber? Fortunately, however, clear epoxy resin readily lends itself to determining the mechanical stresses within it by the photo-elastic technique, and this is an easy way of detecting any stress concentration.

With a component exceeding an 11 kV rating it is also advisable to keep the electrical stress within the resin. For example, with a bushing, this means including foils within the insulation, as has been the standard practice for s.r.b.p. bushings for many years. Both these mechanical and electrical considerations at present limit the use of cast-resin components to about 20 kV. If, however, epoxy resin is used only as an insulating support,

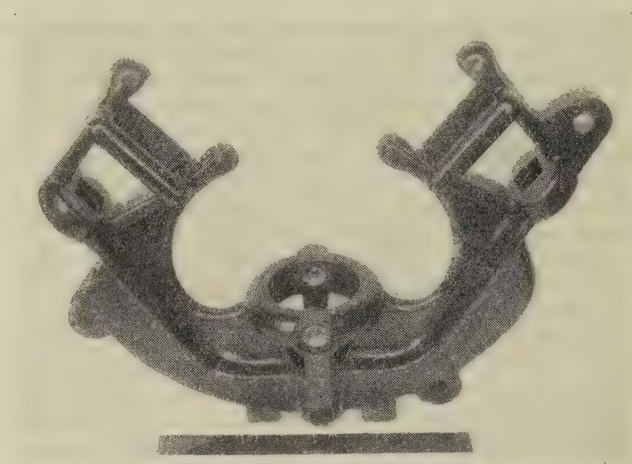


Fig. C.—Cast-resin component of a 275 kV tap-changer.

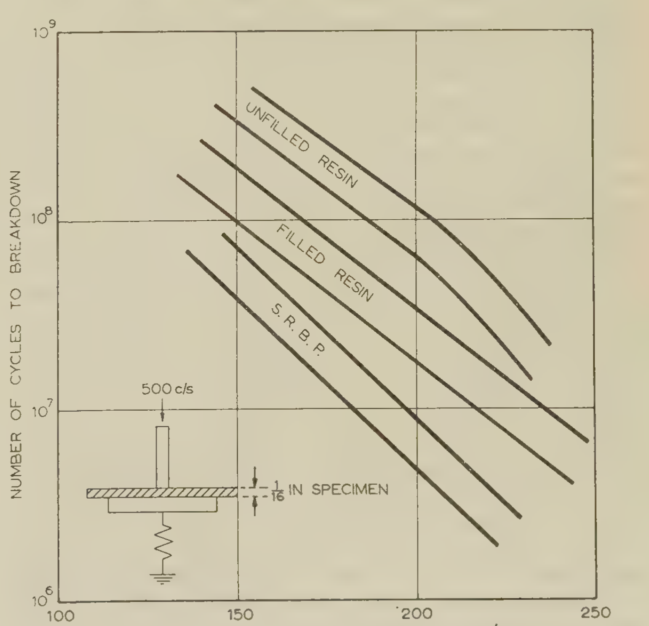


Fig. D.—Voltage endurance of Araldite B and an electrical-grade synthetic-resin-bonded paper at 20° C.

much higher voltage components can be made. Fig. C shows part of a 275 kV tap-changer.

We, too, have not found the variation of the loss angle with voltage a suitable means for checking the electrical quality of a component, and for the past few years my company has used a discharge detector for the routine testing of production components. The acceptable discharge level, however, has been lower than that adopted by the authors, namely 100 pC at 40% above the working voltage. I agree, however, that 40 volts/mil is a safe working stress for an epoxy resin, which has a higher resistance to electrical discharges than synthetic-resin-bonded paper. Fig. D illustrates this. $\frac{1}{16}$ in thick sheets were sandwiched between a plane and a rod electrode, and a 500 c/s voltage applied between the electrodes.

Dr. F. J. Miranda: In Section 4 it is stated that for the present it is uneconomic to use epoxy resin in switchgear for voltages above 15 kV. For cable accessories we have come to the conclusion that it is uneconomic to use epoxy resin below 33 kV. There are a number of reasons which explain this apparent contradiction. Our starting-point is oil-filled cable insulation, which is outstanding in quality, and we use epoxy castings primarily when they give us constructional advantages. It is also necessary to obtain a dielectric strength of epoxy which is comparable with that of oil-impregnated paper. This is more easily obtainable with solids of rotational symmetry than with the complicated shapes used in switchgear.

To avoid cracking on curing, the authors have resorted to the application of a surface layer of p.v.c., but in so doing they have reduced unduly the ionization level. A discharge level of 40 volts/mil is only half that obtainable in air at s.t.p. Such a low value obviously sets a limit on the voltage rating.

A further important point is the comparatively high power factor quoted in Table 1. Whilst the value given for the pure resin is very similar to those obtained with oil-filled cables, it deteriorates by a factor of 7 with the addition of the quartz filler. Have the authors established the causes of the deterioration which they obtain? Possible explanations are the presence of impurities, inadequate drying and inadequate vacuum.

Mr. W. A. McNeill: Epoxy and polyester resins have been available, as the authors state, almost ever since the war and their potentialities have been closely studied.

There have been some reservations in the minds of engineers which have retarded the wholesale adoption of resins. One might mention cost and behaviour under outdoor conditions and the somewhat unreliable performance under impulse voltage tests. The present paper, however, should encourage development. The problem of cost can be mitigated by the use of suitable fillers, but there remains the question of the anti-tracking properties of the surface, and the authors admit that this material is inferior to porcelain from this point of view. This is very obvious when outdoor conditions are considered, but they also infer that there is some concern about the behaviour even under indoor conditions (see Sections 4.3.1 and 4.3.2).

Have they given any consideration to a combination of porcelain and synthetic resin in a manner which would retain the well-known properties of porcelain from the point of view of exposure to surface stressing, whilst utilizing the resins for their properties in other directions? By careful design, porcelain can be introduced into the moulds and the resin cast on, or, for other applications, porcelain can be superimposed as a skin over the resins where it is both exposed to the atmosphere and subject to electrical stress. Another advantage would be the replacement of a fundamentally expensive material by one which is rather more economic.

Mr. R. J. Males: Referring to Table 1, some of the figures do not agree with our findings. Which resin was used? The tracking times seem rather high: I would expect figures of 200 rather than 600 sec, although with present-day formulations, it is possible to obtain such times.

I do not agree with the authors that, at present, epoxy resins cannot be applied economically to voltages above 15 kV. There is more than one method available for providing stress control, and one of these has so far given good results. The science of voltage control lends itself to the use of epoxides. If the lines of stress are plotted, stress shields can be incorporated in the mouldings in the most advantageous form and position. The results of this can lead to the solving of many extra-high-voltage insulation problems. Mouldings for electronic apparatus with a working voltage of 170 kV having a test voltage of 400 kV have been satisfactorily moulded in production quantities, whilst mouldings of 100 kV with stress-control shields have been made satisfactorily.

Work is in progress on the manufacture of moulded 33 kV outdoor circuit-breaker bushings having stress screens incorporated where a porcelain weather shed is used for weather protection. There is every indication that this process can be applied to a 132 kV bushing with considerable economies.

Components having a thickness of $1\frac{5}{8}$ in have withstood a 900 kV (peak) impulse, which demonstrates the suitability of the material for h.v. work. The working stress on this component is 48 volts/mil, which is near to the authors' figure.

Mr. W. B. Robertshaw: The authors rightly draw attention to the importance of the stress-cracking effect around embedded inserts. However, a false impression may have been left as to the difficulty of avoiding these. In fact, much progress has been made in resolving this problem. The stress patterns revealed by polarized light clearly indicate stress concentration around sharp edges, suggesting an analogy with electrical stress distribution around a conductor. It would have been interesting to have seen stress patterns for embedded inserts with rounded edges.

The authors fail to differentiate between deformable and compressible stress-relieving layers. Solid rubber-like materials may be deformed but not appreciably compressed. The use of solid p.v.c. has the effect of rounding off edges and spreading the mechanical stress. There is virtually no overall stress relief and nothing is done to assist electrical stress distribution around sharp edges.

In certain cases, and notably where inserts are large or sensitive to pressure, it is much better to use a foamed rubber, which is compressible. It will be objected that the enclosed gas will ionize in strong electric fields. However, it is a simple matter to apply an electrostatic screen outside the compressible layer before casting. We have used this method with complete success in developing a variety of products. Sharp edges, and hence high mechanical-stress concentrations, are eliminated; the overall mechanical stress is reduced; pressure on grain-oriented cores is prevented, resulting in good maintenance of magnetic properties after casting; expansion of conductors due to short-circuit heating is accommodated; electrical stress distribution is improved; and ionization levels are more than adequate.

We agree that cracks can develop some time after casting. In our experience they are due to locally high stress concentrations which are avoidable by correct design. Once started, they will propagate by a tearing action. There is no mystery about them and we have had no service failures from this cause.

Mr. H. S. Lewis (*communicated*): How was the water added to the epoxy resin in the experiment of Section 3.1.1?

It appears from Section 3 that there is 30% of phthalic anhydride present. This is at the upper limit recommended by the manufacturers of the resin and appears excessive. Is this, however, a deliberate measure to combat the amount of hardener

hich will be pulled off when pouring at 1 mm Hg? If this is quite a large amount of hardener vapour will reach the acuum pump. How have the authors prevented this?

Do the authors consider that one test point is adequate for assessment of internal discharge? I prefer to have two test points at different voltages as indicated in Fig. E. As the

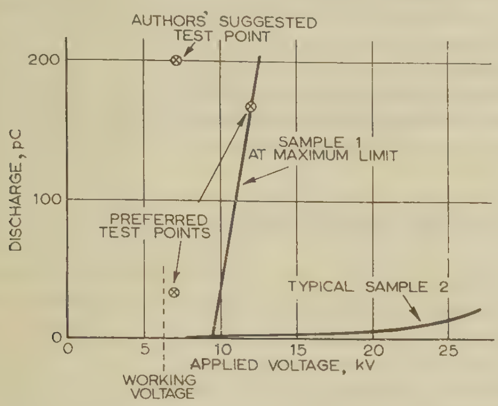


Fig. E.—Discharge/applied-voltage curves.

authors have indicated, too low a limit can be uneconomical, but my company has found no difficulty in maintaining the chosen values, and, in fact, more than half the components have no detectable discharge at the working voltage. Will the authors comment on the two curves shown?

Mr. B. L. Capper (*communicated*): Fig. 4 appears to show certain inconsistences. The contraction shown at 130° C is higher than that shown for the two other temperatures and at the same time total curing contraction is said to be 1·5%. Are we to assume that full curing occurs only at 130° C, since contraction must bear some relation to curing?

With regard to elastic covering of inserts, either by the use of p.v.c. or other materials, what are the authors' views on the mechanisms involved? As such material is totally enclosed by resin, it would appear to be compressed into a solid state. Few homogeneous materials in such conditions can be regarded as elastic. Do the authors consider that the elasticity is provided by minute inclusions of gas? If so, is there any danger of electrical discharge during the working life of the component, as the elastic covering is likely to be in a position of maximum electrical stress?

The above problem may have some bearing on the figure of 200 pC mentioned by the authors as an acceptance limit on electrical discharge. While it is appreciated that even 200 pC represents a very small discharge, there is some weight to Mr. Cherry's argument that it is desirable to have no discharge at all at the working voltage. Apparatus is available which will measure discharges less than 1/2000 of this value and the policy of my company is to reject components which have a discharge much smaller than that suggested by the authors. Are the authors able to relate magnitude of discharge and component volume to the expected life of the component?

Mr. C. F. Stone (*communicated*): An interesting phenomenon has been noted during discharge tests on cast-resin transformers produced by my company. If the corona extinction voltage is measured by reduction from the ignition value, and then the voltage is increased again (say to 30 kV for a 6·35 kV working sample) and held for 60 sec, the corona extinction voltage is then found to be lower than that originally measured. Resting for a few hours restores this to its original value. Have the authors observed this and have they any explanation?

The stress level of 40 volts/mil given is of interest. Is this an average figure computed from the total applied voltage and thickness of material, or is it the maximum local stress near the boundary of the conductors?

When dealing with short-circuit performance the authors state that temperatures in the region of 200° C are experienced in the copper. Could they indicate what effect this has on the elastic covering and whether there is the possibility of voids appearing subsequently? In this connection it is surely debatable whether the space taken up by the elastic covering would not be put to better use by enlarging the copper cross-section.

Mr. A. J. Coveney (*at Leeds*): The information given regarding internal mechanical stresses could be simplified by a curve showing safe permissible distances between conductors at different voltage levels.

The practice of wrapping conductors with polythene tape invites discharge damage due to 'trapped air', and a condenser layer winding to safeguard possible breakdowns would provide a long-term safety feature in these mouldings.

As it is important that grease of any nature must be avoided, are any special precautions taken to remove this from the hand-wrapped p.v.c. covering?

With regard to the use of glass fibre, would not a glass fabric be a more satisfactory reinforcing material?

The use of wedges as fixing supports appears to be a potential weakness unless the curing temperature is carefully controlled due to unequal shrinkages that might occur. The method of curing-temperature control appears to be a matter of some importance, as a gradual hardening process is most essential to prevent any voids left in awkward spots in the moulding.

Referring to varying surface conditions, a static charge is often left on these mouldings which could upset any power-factor testing now adopted on site as a method of determining any ageing of insulators. Can the authors comment?

According to C.I.B.A. reports, Araldite resins, when used with hardeners, can cause skin troubles to operatives, and this is obviously something against which manufacturers must take special precautions. What can the authors tell us on this subject?

Mr. A. R. Rumfitt (*at Leeds*): The authors draw a comparison between the limited properties of conventional types of insulation and the fact that the epoxy and polyester resins are available in forms which embrace all the desired features listed by them.

They do not emphasize, however, that in the manner of their application the use of the resins calls for a new concept and that the materials are used to provide, not only the insulating requirements in a particular project, but also to give the necessary mechanical security. In one large moulding, therefore, a number of vital components are embodied and this poses the question as to the desirability of having so many features depending upon the security of a single moulding. It is axiomatic that by reducing the number of components to be assembled in the manufacturing stages the degree of maintenance is thereby reduced, but thought must be given to the problems which will subsequently arise when component replacement is required in service.

In considering the assemblies illustrated in the paper it is obvious that damage to a small item can involve the replacement of a complete moulding, the value of which will be many times the value of the damaged part.

The figure of 200 pC is quoted as a reference discharge level at 15% over-voltage. Can the authors give some indication of the inception and extinction voltages and the upper magnitude of those discharge levels which exceed 200 pC?

The authors refer to future developments in which reinforced

resin circuit-breaker tanks may be envisaged and to other applications wherein earth metalwork can be completely omitted. As the acceptance of such techniques would be in complete violation of the normal standards accepted for metal-clad switchgear, have the authors any observations on this aspect of their researches?

Mr. E. C. Rippon (*at Newcastle upon Tyne*): With solid insulants two approaches are possible: to design to a discharge level which life tests and experience have shown to be innocuous; and to design to ensure that there is no corona discharge at the working voltage, or at even higher voltages if service conditions demand this. I prefer to adopt the second approach.

The authors mention that a number of components manufactured from epoxy resins are undergoing duration tests but they do not give any significant information. Presumably the applied voltages are much higher than the working voltages of the parts under test. Whilst the magnitude of the discharges are stated to be in excess of 200 pC, is this meant to convey fractional increases above the acceptance discharge level or discharge figures approaching, say, 2000 pC? Figures must be stated if the duration tests are to have any meaning, despite the authors' assurance that, at present, there is no evidence of any deterioration.

Have the authors had any experience of accelerated discharge testing techniques, whereby voltages are applied at much higher frequencies to reduce the overall time of life testing?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. T. R. Manley, K. Rothwell and **W. Gray** (*in reply*): *Mr. Cherry*.—The discharge limit of 200 pC at 15% above the working voltage was chosen because at the time when production of resin articles commenced it was the limit used by a large number of bushing manufacturers. This limit was determined from the tests and examination of a large number of bushings which had been in service for many years. Since discharges of less than 1 pC can be detected with modern equipment it is uneconomic that there should be no measureable discharge at the working voltage.

There is no reason to believe that the process of degradation of cast resin under discharge is essentially different in its effects from that of resin-impregnated paper. Discharges produce microscopic breakdown paths and the products of this breakdown cause further deterioration of these initial paths. It has been observed that with a fairly large void a resistive coating from the breakdown material has formed on the walls of the void decreasing local stress to such an extent that discharges have ceased altogether at the previous inception voltage. Under these circumstances there is no further degradation. As for the rate of degradation at high internal discharges, it depends on whether the discharge measured is an average figure for the total mass of the insulation or refers to one single void. In the last case one might expect thermal instability and greater rate of deterioration.

Mr. Garrard.—We are aware that p.v.c. will deteriorate in air at temperatures in excess of 120° C, and also that this process is inhibited when p.v.c. is embedded in epoxy resin. No signs of deterioration have been seen in service. We have not found that traces (less then 0·1%) of ferric oxide have a significant effect on the properties of the finished article. The joints referred to are made with a cold-setting silica-filled polyester resin.

Mr. Care.—There is no objection to the use of foamed rubber with a metallized screen, provided that there is no possibility of the resin penetrating the rubber, which could tear the resin during the curing.

We consider that, except for certain articles such as voltage transformers, it is not economical to use resins above 15 kV because of the difficulty in providing adequate stress control layers.

Mr. Brown.—Although polyester-bonded glass materials are not recommended where resistance to radial stress is required they are extremely useful materials. They may be used where surface stress only is encountered, such as in busbar supports, and for low-voltage applications, such as plugs and sockets. Polyesters provide the most economical method of impregnating 11 kV voltage transformers.

Mr. Davies.—We agree with Mr. Davies's initial comments. With regard to Fig. 2, this work was performed because of difficulties in production, due to absorption of moisture by the hardener, which indicated the necessity of closely controlled storage for the raw materials of the process.

Mr. Stark.—The work at 300° C mentioned in the paper was done using p.v.c. It should be noted that this was the copper temperature and was of a transient nature.

Mr. Males.—The resin used in Table 1 was Araldite B with phthalic anhydride. The tracking figures were obtained using a standard E.R.A. test set.

Mr. McNeill.—In certain circumstances the mounting of a porcelain insulator over an epoxy bushing gives good results.

Mr. Lewis.—In Section 3.1.1 water was added to the phthalic anhydride by means of a semi-micro burette. The anhydride is very much more hygroscopic than the resin. The amount of phthalic anhydride used (30%) is not critical. Most of the hardener vapour is trapped before reaching the pumps, thus reducing maintenance of the latter.

We agree that one test point is inadequate for the assessment of internal discharge. In practice we rarely experience discharge at 15% above the working voltage. However, when discharge does occur a curve is plotted similar to that in Fig. E. Should the discharge/voltage characteristic be a steep curve, as with sample 1, the article would be rejected.

Mr. Capper.—In Fig. 4 only the initial part of the curing contraction is shown. In fact, resins may be cured at any of the temperatures given provided that they are kept at the temperature for a sufficiently long time. It can be seen, however, that the rate of contraction in the initial stages is much higher at higher temperatures. The figure of 1·5% for contraction is the mean of several results. The mechanism of the use of p.v.c. is to prevent the resin adhering to the copper and also to relieve the radial stress. In the illustrations the p.v.c. is totally enclosed but in practice it usually protrudes from the resin and consequently allows it to be further deformed.

Mr. Coveney.—Dermatitis is not caused by epoxy resins but by amine hardeners. Most of the resins mentioned in the paper are cured by anhydride hardeners. Skin troubles may be avoided by the use of barrier creams and masks where appropriate.

Mr. Stone.—We have experienced the phenomenon described by Mr. Stone, for which a possible explanation is that the relatively prolonged discharge within a void deep in the material produces a polarizing effect, thus causing a reduction in the voltage required for ignition. Resting the specimen would give time for the polarizing charge on the void surface to leak away. The stress level of 40 volts/mil is an average figure.

Mr. Rippon.—We have carried out discharge life tests on small samples at frequencies in the region of 2 kc/s and the results

agree generally with those of other authors.[4] We are now testing resin production articles, and although these tests are not complete, it is interesting to note that an 11 kV current transformer energized at 7·6 kV to earth, discharging at 700 pC, has been on test for an equivalent 50 c/s life of 6 years. A similar current transformer has been on 50 c/s voltage duration at 7·6 kV to earth since May, 1955, with a discharge extinction of kV and with a level of 600 pC at the test voltage.

Mr. Rumfitt.—If damage is caused to a resin assembly by a power arc then, in our opinion, the replacement cost would be no more than for a conventional compound-filled unit. However, if slight mechanical damage occurred at a point which is not in the region of high electric stress, a repair would be possible using a cold-setting resin.

We agree that completely resin-insulated switchgear equipment is not normal practice in this country. However, it is now being used on the Continent and the experience so far has been good.

Dr. Miranda.—With regard to the power factors given in Table 1, it should be noted that the level is not significant at power frequencies. However, it is important that the power-factor/voltage curve shall remain flat within a temperature range of 0–90° C.

Dr. Mason.—We agree that for a given discharge in pico-coulombs the process of degradation is more rapid with increased electric stress. This is consistent with the increasing stress raising the electron energy so that more damage is caused for a given charge.

With regard to the effect of temperature on the rate of deterioration, the rise in temperature will be lower in epoxy resin than in s.r.b.p. This is due to the higher thermal conductivity and lower dielectric losses of epoxy resin compared to s.r.b.p.

DISCUSSION ON 'THE DESIGN OF THE 330kV TRANSMISSION SYSTEM FOR RHODESIA'*

Before *the* East Midland Centre *at* Nottingham 21*st October*, *the* North Midland Centre *at* Leeds 4*th November*, *the* North-Western Supply Group *at* Manchester 25*th November*, 1958, *the* South Midland Centre *at* Birmingham 5*th January*, *the* Western Centre *at* Cardiff 12*th January*, *the* Northern Ireland Centre *at* Belfast 10*th February*, *and the* Western Supply Group *at* Bristol 20*th April*, 1959.

Mr. O. W. Nutt (*at Nottingham*): It is particularly interesting to consider various design aspects mentioned in the paper in relation to operational experience of the 275 kV Grid system which has been obtained in the East Midlands Division.

The decision to use single-circuit line construction was influenced largely by the fact that this type of construction would require smaller towers than those needed for double-circuit construction and that these smaller towers would be less likely to be affected by lightning.

There is considerable evidence to support this theory from our experiences with the 275 kV system. The lightning fault frequency has been much higher than anticipated so far, and figures for the past three years give rather surprising results:

Year	132 kV faults per 100 miles	275 kV faults per 100 miles
1956–57	0·8	1·0
1957–58	1·4	2·6
1958–59 (to date)	1·5	1·0

These figures are for the East Midlands Division only, and must be influenced by the distribution of the lightning storms in relation to parts of the area having concentrations of 132 and 275 kV lines.

In the three years referred to there have been 25 lightning faults on the 275 kV lines, of which 24 were on lines of double-circuit construction. It is probable that none of the faults involved both lines on a double-circuit tower. This experience makes one wonder whether the economy of this construction does not outweigh the apparently small risk of a double-circuit outage. However, the tower footing resistances are generally low in this part of the country, an average figure being 2–3 ohms.

What type of accelerating signal is used in connection with carrier acceleration of distance protection? On the Swedish system, where the carrier channel is also used for indications, metering, communications, etc., the accelerating signal is produced by a momentary suppression of the carrier. I understand that this has not been very successful, possibly owing to interference generated by the fault arc.

It will be very interesting to obtain operational experience of the single-phase high-speed auto-reclosure which is proposed, as it seems that the length of line involved may be about the maximum for successful arc extinction. High-speed 3-phase auto-reclosure on the 275 kV Grid system, with a 'dead' time of 0·35 sec, has recently been introduced on the Staythorpe–Elstree circuits, but experience has so far been limited to only two operations, one successful and the other unsuccessful. Do the authors know of any field experience to suggest that single-phase high-speed auto-reclosure is likely to be satisfactory on 330 kV lines 150 miles or more in length?

In a number of cases single-phase transformer units are used instead of 3-phase units because of transport difficulties, and a single-phase unit is provided as a spare. When this arrangement is adopted, is it possible to bring the spare unit into service without an outage of the 3-phase bank?

Mr. W. J. A. Painter (*at Leeds*): My first impression is that the design of the system has not followed the more usual practice of co-ordinating power supplies to meet defined loads, but has been based on the need to distribute the output of Kariba power station. This approach may have influenced the acceptance of single-circuit security risks.

The next impression is that the authors tend to give statements of decisions without the reasons governing them. The breakdown of the capital costs given in Section 2.2 and in Fig. 3 between lines, substations, etc., would have assisted in appreciating the choice of voltage. No reasons are given for the choice of bulk-oil circuit-breakers in preference to air-blast circuit-breakers; certain advantages can be attributed to each type, but what were the deciding factors in this case? Why were oil-filled cables used in a situation which would appear to favour gas-filled cables?

I suggest that, in the final scheme, 3-phase auto-reclosing would be more satisfactory than the single-phase scheme adopted, and I should like to know the reasons for the choice. The C.E.G.B. have recently installed two trial installations of 3-phase

* Winfield, F. C., Wilcox, T. W., and Lyon, G.: Paper No. 2583 S, March, 1958 (see 105 A, p. 580).

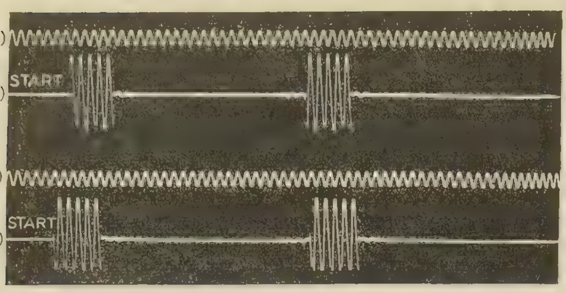
(a)
(b)
(c)
(d)


Fig. F.—Monk Fryston—Stella 275 kV auto-reclosure, 10th June, 1958.
(*a*) and (*b*). Stella 1. (*c*) and (*d*). Stella 2.

auto-reclosing on the 275 kV system in this country. Fig. F shows typical test results on the one in this Region for a type of circuit-breaker similar to that used in Rhodesia. Waveform (*a*) is a 50 c/s timing trace, and (*b*) is the current in the telephase protective equipment under simulated persistent fault conditions. The fault current persists for about five cycles whilst the circuit-breaker contacts open, followed by two cycles of much reduced value whilst the resistors are opened; there follow 16 cycles of 'dead' time, pre-arcing current, fault current, retrip and lock-out. Waveforms (*c*) and (*d*) are similar records for the second circuit. I trust that the authors will, in due course, make available the records of the tests which, as stated in Section 3.3.1, they propose to make.

In connection with Section 4.3.1, it seems unfortunate that the generator output is not being transmitted automatically with the line load-flow telemeters.

Mr. F. V. Dakin (*at Manchester*): Whilst the total cost for the 1 200 MW scheme is given as £113 million, which comes to £94 per kilowatt, the cost of transmission is given in Fig. 3 as £36 million which comes to £30 per kilowatt. In view of the high cost of transmission, it would appear that d.c. transmission, where economics favour the longer distances, might be the answer. There are two other factors which suggest that there may be advantages in using direct current. First, the thermal stations seem ideally disposed for providing reactive power at the receiving end of the lines, and secondly, the system is interconnected to the U.M.H.K. system in the Belgian Congo. The authors state that 'the interconnected system so formed' will have a length of about 1 000 miles, including one or two rather weak links, and interesting operating problems will arise. I suggest that these problems may prove to be headaches.

The economic comparison of the voltages for transmission has been carried out over a period of 11 years. In view of the very high increase in load growth (3 500 MW by 1980) I suggest that the economic comparison should have been carried out over a 20-year period. Is it possible to uprate the 330 kV lines to 380 kV if necessary?

In comparing the incidence of expenditure for the schemes at different voltages, the authors state the 'the limits set to the transmission of power by the possibility of transient instability were low enough to control the development of the system at some stages'. Has consideration been given to the use of mesh-type rather than double-busbar switching arrangements at intermediate stations? This would involve the loss of only one line instead of two for a busbar fault and would thus improve the stability of the system.

The authors state that it is unrealistic to design a system to withstand the effects of a 3-phase fault on a major line, as faults should be rare with the configuration and spacing assumed. Trouble has been experienced in this country owing to human-element faults leaving earths on the system. Do they consider that the chances of this happening in Rhodesia are much less, or are the economic consequences not so great?

On what do the authors base their statement that the incidence of faults will be lower as the transmission voltage increases, since experience has proved in this country that the incidence of faults on the 275 kV system is higher than on the 132 kV system.

I note that high-speed distance protection is being used for the lines. This will involve the use of capacitor voltage transformers, and trouble has been experienced in this country when distance protection has been used with 275 kV capacitor voltage transformers. Are the authors satisfied that the difficulties when utilizing this type of voltage transformer have now been overcome?

Mr. G. E. Woodhead (*at Manchester*): The authors have received a great deal of criticism for choosing a non-standard voltage, but, in my view, they may quite well be justified in their choice. On a scheme like this, about 75% of the total expenditure is on overhead lines. When a long mileage of line is involved there is nothing to be gained by insisting on a standard voltage. A line could quite well be designed for any voltage, and considerable savings are possible if the right one is chosen. Standardization of voltage is really of advantage only on substation equipment, and in this instance I do not see how even the terminal equipment could be standardized.

If 275 or 380 kV had been selected I presume the insulation in air (bushings, etc.) would have to be non-standard because of the altitude at which the equipment is required to operate. In the event it is the economics which decide the question, and I am sure the authors agree that it is better to have a non-standard client who is solvent rather than a standard client who is broke.

It is interesting to learn that, as a result of extended stress/strain tests on the proposed conductors, the correct over-tensioning allowance has been arrived at. In this country we do not seem to be in such a happy state of mind, and, in fact, country-wide observations are going on at present to determine how far s.c.a. conductor drops after sagging.

It is true that economic span curves are fairly flat near their minima, and in view of this, perhaps something other than economics should have dictated the standard span length. There might be some advantage in a country where the lightning hazard is high in having shorter spans, giving reduced tower heights and more earth connections per route mile.

Was the use of standard angle sections laid down in the specification, or were tenders allowed to consider, say, tubular sections? If the latter applied, was a tubular tower rejected on purely economic grounds?

Mr. C. H. Flurscheim (*at Manchester*): The authors specify a 4-cycle total break time for the 330 kV circuit-breakers, which, by modern standards, is slow. Can the value to the network of shorter break times be capitalized, based on improved stability performance? Three-cycle interruption is now afforded by some designs throughout the current range, and it would be of interest to know if there is a real need for still shorter times, which might require more complicated and expensive mechanisms.

The authors have selected vertical-break isolators, which are in general use in the United States, despite their increased basic cost compared with the horizontal twin-rotating-arm units, which are standardized for the British 275 kV network and in general use in Europe. This selection is based on economy in site area made possible by using vertical isolators, with consequent reduction in levelling for this particular substation.

Would the authors prefer the vertical design for substations where area is inexpensive in terms of purchase of ground or cost of levelling operations?

Mr. G. S. Buckingham (*at Birmingham*): We have heard a great deal of the water power in Sweden being carried down

the whole length of that country; water power in Russia being carried long distances and at very high voltages; the Kitimat scheme in Canada and the Snowy Mountains scheme in Australia, and now we have the Kariba scheme. This must surely be the last of the international hydro-electric schemes, because any future ones are likely to consist of nuclear power stations; but when we consider the costs quoted in the paper it must be agreed that they are very low considering the enormous engineering project they represent and the large power output being obtained from the River Zambesi at Kariba. The figures represent only £64 per kilowatt of generation and something like £36 million total cost for the transmission system as a whole. They are very low and reflect great credit on the authors.

It would be interesting if we could look into the minds of the authors and discover some of the fundamental reasons which persuaded them to take certain steps in the designs. 330kV is a secondary preferred standard for high-voltage long-distance transmission. The paper provides some of the comparisons of cost which have influenced the authors, and I think they will say that the high altitude of the lines above sea level means that insulation levels provided are such that they would be suitable for 380kV, the primary transmission voltage, if the lines were near sea level. It is therefore possible that we shall obtain some first-class operational experience with equipment designed for the top transmission voltage anywhere in the world.

In Rhodesia the isoceraunic level is 60; in the Midlands it is just under 10, and still 60% of our faults are due to lightning. If the problem of interruptions due to lightning has been solved in Rhodesia it must be regarded as a very great achievement.

Why have the authors rejected radio for the main communication system? The problem of overcrowded wavebands cannot be as bad in Rhodesia as it is in this country? One would imagine that there is plenty of room for additional high-frequency channels which might have given communication links free from broken conductor trouble.

Is there a fire risk in the summer? Even in this part of the world we have trouble from heath fires in parts of our rural area. They cause much inconvenience if the necessary steps are not taken to overcome them.

Mr. L. L. Tolley (*at Birmingham*): Towards the end of the paper it is mentioned that communication is by carrier, and it is also mentioned in the paper that, if there is a fault on the circuit, there will be no alternative route on radial circuits served by a single line. This means that, where there are not two circuits on the tower, there will be no alternative route. From Fig. 2 it seems that, for about five years, there will be no alternative communication on several routes, and some stations will have no alternative communication until about 1972. This really refers to Mr. Buckingham's point, namely the possibility of ploughing in telephone-type cable along the wide swathes. Post-Office type cables should not be used since, with these long parallel lines close to the transmission line, the voltage induced would be appreciable if there were earth faults.

Mr. I. G. Edwards (*at Birmingham*): At the Kitwe end of the Kariba system there is a 330kV line entering, and there is an existing Belgian Congo 220kV line coming from the other side. I presume that, at some period, it will be necessary to run the two systems in parallel. If so, what arrangements have been made for phase-angle control? Owing to the long transmission distances involved, the phase displacement at Kitwe should be fairly large, and therefore, if no phase-angle control is provided, paralleling of the two systems could be carried out only when loading conditions are such that minimum phase displacement occurs. Presumably the circulating currents between the Belgian Congo and Rhodesian systems could be quite large, even for small displacement angles.

From some of the figures given in the paper the back flashover voltage per 100 miles per annum increases very considerably as the tower footing resistance increases. In a previous paper it was suggested that while, as a generalization, the tendency was for towers with high footing resistances to be more susceptible to back flashover than ones with low footing resistances, practical investigation of lightning faults of this nature over a period of years showed that about 50% of the total back flashovers were on towers having fairly low footing resistances (10 ohms or below). In the initial stages of the Kariba scheme, security of supplies will depend on single-circuit lines operating in territory having a high isoceraunic level. All practicable precautions have been taken to protect the line from direct lightning strokes, but, in view of the high soil resistivity expected at many places along the route, can footing resistances be reduced sufficiently to make flashover a comparatively negligible quantity?

Mr. J. S. Cliff (*at Birmingham*): The voltage used has already been criticized on the ground that it is not a standard I.E.C. value. When the next voltage step above the 275/300kV level was considered by the I.E.C., the Swedish 380kV system had already been planned, and as it was likely to be connected to systems in other European countries, this value was standardized, with a highest system voltage of 420kV. Despite the very considerable increase in cost compared with apparatus for 300kV, no agreement could be reached on an intermediate voltage. It was not suprising that an intermediate voltage soon appeared, namely 330/345kV in the United States. This was followed by the 330kV Snowy Mountain scheme in Australia, and now the Kariba scheme in Rhodesia. All these schemes have justified their choice of voltage on economic grounds, and as they are each isolated, there seems to be little objection. This intermediate voltage presents no difficulties to the apparatus manufacturer since most of the equipment supplied is, in any case, specially designed. As a result of the practical introduction of the new voltage, the I.E.C. has now decided to recognize it, with a highest system voltage of 362kV, and nominal values of 345kV for systems with 5% regulation and 330kV for those with 10%.

The authors' specification for circuit-breakers covers a wide range of breaking currents of all types, and it has been shown that the bulk-oil circuit-breaker can deal adequately with all these without excessive time delay or arcing times. It is also capable of either 3-phase or single-phase auto-reclosing operations. As a bulk-oil circuit-breaker requires about 20% less area than other types this results in a very appreciable saving in overall cost. In addition to providing space for current transformers on both sides of the circuit-breaker, the condenser bushings can also provide a source for relaying and metering voltages. Will this voltage source be used in the Kariba scheme?

Mr. S. Taylor (*at Birmingham*): A previous speaker suggests that the bulk-oil circuit-breakers selected for the transmission system could not handle evolving faults. The particular difficulty presented by evolving faults is, of course, due to a sudden rise in fault current at a time when the existing arc path in the arc-control pot is relatively long and little gas has been generated within the pot to cushion the consequent massive increase in pressure. The design of an arc control-pot to withstand these conditions presents no difficulty, and tests reproducing the effect of evolving faults are readily arranged.

With regard to high-altitude insulation requirements at Kariba, I understand that these were met by specifying bushing insulators with an increased impulse level at sea level in accordance with B.S. 116: 1952. Such a test must either over-stress the bushing solid and oil insulation or compel it to be wastefully designed to meet the higher voltage. Would the authors agree that a much more satisfactory test would be one carried out at the test

voltage appropriate to the actual site but with the bushing air-insulation path appropriately reduced in length by a temporary downward extension of the bushing terminal chamber?

I note that single-phase auto-reclosing is to be used in parts of this 330kV system. I should have thought that induced voltage in the open line, from the adjacent live lines, would seriously delay the deionization of the fault path. With regard to the separate phase mechanisms for the circuit-breakers to be used for this operation, could the authors state the maximum difference in closing and tripping times which can be tolerated between the phases when switching the 3-phase system?

Mr. J. A. Prescott (*at Birmingham*): The authors refer to some of the lines being equipped with single-phase auto-reclosing on the 330kV circuit-breakers. This is an interesting application of this form of reclosure, and I wonder whether any systems in the world are satisfactorily operating on single-phase auto-reclosing.

It would be interesting to know what times they expect to be able to operate on single-phase reclosing because of the length of the lines and the voltage being employed. Will the arc caused by a flashover to earth on the insulators in fact be extinguished, or will it be sustained by the induced voltage of the healthy phases?

Another point of some interest is the use of circuit-breakers between the generators and transformers on the 18kV side. This is rather unusual in this country but fairly popular abroad. It is a special circuit-breaker, certainly in this country for use on 18kV, and I imagine that the rating would be 3·5kA. It would be interesting to know whether air-break, air-blast or bulk-oil circuit-breakers have been adopted and what short-circuit rating is necessary.

It is evident that the electrical connections at the top of the isolators were equipped with vertical corona rings, which are usually associated with the means for reducing radio noise. What radio noise level, if any, is being applied on the Kariba system in terms of microvolts at the maximum phase-to-earth working voltage?

Mr. C. T. Baldwin (*at Cardiff*): Can the authors give any information on the estimated corona loss for the line? This would be of interest in view of the difference between climatic conditions in Rhodesia and this country.

Section 5.3.4 could be taken to imply that the outer conductors only are transposed. Is this so, or are normal cycles of transposition used? How many cycles of transposition occur in each section of the line?

Mr. A. H. McQueen (*at Cardiff*): I note that the estimated 16% load growth over ten years was considered to be high and that it was later reduced. I am surprised at this; one would have thought that, in a rapidly growing country, the load growth would be on an increasing rather than a decreasing scale for some years to come. It is noted that financial stringency had to be applied in the early stages of the project. It is always a mistake to do this since it is usually more difficult to obtain money later on. In consequence, the engineering work suffers throughout the lifetime of the installation, or it costs very much more to improve later.

Bulk-oil circuit-breakers were chosen for the schemes. I should have thought that transportation, erection and maintenance would have been simpler if air-blast circuit-breakers had been used. These would possibly have been easier to arrange for single-pole auto-reclosing, and one would expect more rapid deionization and therefore faster reclosing with possibly improved system stability.

The system is not designed to withstand the effects of a 3-phase fault on a major line. No doubt there are very good reasons for this, but one would have thought that there is a possibility of a 3-phase fault due to lightning or a broken line, particularly if a long line came down and wrapped itself around the other lines. What would happen in this event?

The choice of voltage may represent an intermediate stage. Do the authors visualize an increase in this voltage, and what arrangements have been made on the lines and substations to cope with it?

Mr. G. Minter (*at Cardiff*): The basic design of the Kariba system is relatively simple if one compares it with the system design problems encountered in more highly developed countries, but this is offset by the severe economic restrictions imposed on the designers during the early years of a scheme in which moderate amounts of energy have to be transmitted reliably over long distances in a very bad lightning area. Nevertheless, the authors were clearly up against the usual uncertainties in considering their basic design. For example, the common practice of scaling down the long-term load estimate because it was thought prudent to do so has been followed in this case, and since there are already signs that the load estimates are conservative, a major reinforcement of the system may be necessary at an earlier date than was envisaged.

Very little information is given in the paper on the requirements for new generating plant after the completion of the Kariba scheme, but, assuming that a fair proportion of the thermal plant will become obsolescent during the next ten years, it appears likely that a large new station will be required before 1971. The authors apparently have no knowledge of which of the possible sites mentioned in the paper is next on the list for development, and yet, as they remark, the influence on transmission development could be profound. It thus appears that the authors have not been in a position to look forward, except in a very speculative manner, for a period of more than ten years after the commissioning of the scheme. No designer would have been entirely happy in these circumstances about the choice of voltage on a scheme, which, however simple initially, seems to have very great potentialities. If, as the authors suggest, a 380kV scheme were ruled out because of initial capital limitation, it would still have been of considerable interest to have included its cost of development in Fig. 3. Do the authors think it possible that the long-term development of the scheme may have been seriously influenced by the development charges on 380kV equipment in the early stages?

I have not been able to form any accurate impression of the load factor of the Kariba station or of the operation of other generating plant, but it seems likely that there would be periods when the Kariba station could carry all or nearly all of the load on the system. I would therefore be interested to know whether the studies included an examination of the voltage-stability problem which may exist following the clearance of a 3-phase fault on the 220 or 66kV system under these conditions. The Table in Section 4.1 indicates a heavy motor load with a high load factor in that area, and 'out of merit' operation of the local generating plant may be necessary in order to avoid voltage instability after the clearance of a fault.

The authors have apparently laboured under the usual handicap of insufficient time in which to make a detailed technical and economic comparison of the alternative schemes. It is unfortunately so often a fact that, by the time the essential information is reasonably firm, there is insufficient time to give adequate consideration to a large scheme if it is to be commissioned in time.

Mr. W. Szwander (*at Belfast*): The rate of load growth used in Table 1 of the paper is of the order of 8% per annum. This figure appears low when compared with the actual rate of almost 14% per annum during the last 20 years for Northern Ireland rural areas (excluding the cities of Belfast and Londonderry).

The choice of the transmission voltage was, of course, the main problem. While fully understanding the basis on which the choice of 330 kV was made, one is rather surprised that the costs for the 380 kV development should have been 'substantially' higher (and it is unfortunate that relative data are not given in Fig. 3). On the other hand, reference to a recent Russian publication* confirms the suitability of 330 kV. For the 467-mile Kariba–Kitwe transmission system, according to this source, 220 kV would be the economic voltage for loads of up to 200 MW, and 500 kV for loads exceeding 550 MW, whereas, for the anticipated load of 445 MW, 330 kV would appear to be justified. This, of course, does not prove that 380 kV would not be even better. With unavoidable dependence on single-circuit lines, and in a country where the lightning is such an important consideration, it would appear that the possibility, referred to by the authors, of halving the frequency of flashovers per 100 miles per annum when going from 330 to 380 kV should also have weighed considerably in favour of 380 kV.

With reference to the authors' statement that single-pole auto-reclosing is little used, is it not in fact used extensively in the French 220 kV system?

It seems very odd that the station transformers in Fig. 5 are solidly connected to step-up transformers without intervening circuit-breakers. A fault in the station transformer will result in the loss of 200 MW of generating plant. Has not an arrangement of off-load switching for the spare single-phase transformer unit at Kariba been considered?

What provisions were made to cope with high static oil pressures in 330 kV cables at the bottom of the 500 ft vertical shafts? Has the use of single-phase 3-winding 330/220/66 kV transformers at Kitwe not been considered? The cost of laying and the extent of application of the counterpoise along the transmission line would be of interest.

Have any compensation payments had to be made for the transmission-line rights of way? If so, how do they compare with British figures? The same question applies to the huge lake created by the Kariba dam. Is it not fair to assume that such a scheme is possible only in an area like the heart of Africa?

Mr. A. A. T. Bowden (*at Bristol*): Were the 330 kV oil circuit-breakers used at the Kariba site because of space considerations only, or was the increased complexity of maintenance (for air-blast circuit-breakers) a factor taken into account for a somewhat remote site?

What type of 220 kV booster is being employed? Has the Jansen type of auto-transformer tap-changer been used?

It is of interest that air-blast circuit-breakers were developed in France in 1928. Individual-pole operation was current practice in 1939 for the north–south 220 kV transmission line.

What are the prospects of e.h.v. d.c. transmission? Cannot the vast mechanical circuit-breakers be replaced by the more elegant switching by electronic grid control of the rectifier-inverter units?

Messrs. F. C. Winfield, T. W. Wilcox and **G. Lyon** (*in reply*): We propose to group our comments under the appropriate sections of the paper.

Power Demands (*Section* 2.1).—The tapering down of the load-growth estimates which has been criticized is not quite so dangerous as it might appear. Once the rate of growth of load on the first phase of construction has been established, there should be no major difficulty in accelerating the construction of subsequent stages to meet higher rates of load growth if necessary.

Prospects for further development beyond the completion of the Kariba scheme are necessarily conjectural, and we do not consider that it would be wise to spend additional capital now with the uncertain prospects of saving a marginal sum in 15 or 20 years' time. It has now been established that the Kariba 'B' Station can have a capacity of 900 MW, giving a total installed capacity of 1 500 MW, and also that it will be economical to construct the Kafue River scheme, which will give an additional output of about the same magnitude. The 330 kV transmission system described in the paper can be economically developed in stages to handle the whole of this 3 000 MW.

Choice of Voltage (*Section* 3.2).—The proportion of the initial expenditure of £80 million represented by transmission costs is approximately £14 million, and this is made up of approximately 65% for overhead lines, 11% for step-down transformers and reactors and 24% for substation equipment.

It is difficult to judge whether a d.c. transmission scheme might have shown an advantage in cost over the a.c. scheme, because, even at the present time, reliable estimates of the cost of d.c. terminal equipment are not available. A d.c. transmission scheme could only have been contemplated as an experiment, and we did not feel that this could be justified on such a large project which is of vital importance to Rhodesia. Instead we have recommended an a.c. scheme, but we realize that it may become advantageous to partially convert or extend it into a d.c. scheme at a later date when suitable terminal equipment becomes available.

Although the economic comparison covers a period of only 11 years from commissioning, it represents 16 years from the planning date. We believe that this is a sufficient period to consider in countries such as Rhodesia, which combine high rates of growth with relatively short previous load records.

A number of speakers have criticized the omission of costs for 380 kV in Fig. 3. Our early studies showed that an increase in voltage above the 220 kV proposed in 1951 would be beneficial, but that the carrying capacity of a single 380 kV line would be technically adequate for perhaps as long as 20 years on the Bulawayo route. Consequently additional circuits at 380 kV would be required purely for security reasons, and the provision of this security would render the cost of a system at 380 kV substantially greater than that at 330 kV. Although the predicted number of lightning outages at 380 kV is about half that at 330 kV, this is not the only cause of outage, so that the overall reliability of a single circuit is not in a 2 : 1 relationship.

Single-Pole Auto-Reclosing (*Section* 3.3.1).—At the time of writing the paper the only field experience of single-pole auto-reclosure at voltages above 300 kV of which we knew was the Swedish and Russian work referred to. In the last few days of 1959 we conducted a series of tests on the Kariba–Kitwe line in which single-phase faults were applied at various points by releasing fuse wires to produce insulator flashovers. The lengths of line switched were 90 and 180 miles, the fault currents were all less than 1 kA, the 'dead' time of the circuit-breakers was 0·5 sec and wind conditions were light. Preliminary reports from site state that all single-pole auto-reclosures were successful. Further single-phase tests at different fault locations and other line lengths, fault currents and 'dead' time settings are expected to take place soon.

Insulation Levels (*Section* 3.5).—The over-voltage testing of equipment for use at high altitudes has been discussed by both national and international committees for many years, and we agree with the method adopted in British Standards although we recognize its advantages.

Mr. Taylor's proposal of artificially lowering the live metal of a bushing terminal should be quite satisfactory in some cases, but, in many others, the internal voltage distribution of the bushing would be affected, and for this reason the method is not suitable for universal application.

* Krachkovskii, N. N.: 'Where and Why the Use of 330 kV as Transmission Voltage is Advantageous', *Elektrichestvo*, 1958, No. 10, p. 72.

System Control (*Section* 4).—It is expected that the Federal Power Board and Belgian Congo Systems will operate permanently in parallel from the outset, and our studies have shown that the load swings between them should not be excessive. It will be necessary for one system to accept the duty of regulating frequency and the other that of regulating power exchange; phase-angle control at Kitwe is not necessary for this purpose, as it can be achieved by generator governor control.

We agree with Mr. Minter that during the early stages there is a likelihood of system instability, falling frequency and low voltage in the Copper Belt following the clearance of a 3-phase fault in that area. For such reasons it is probable that the automatic load-shedding facilities which have been in use for some years for the 220 kV supply will need to be extended. In this event our studies have shown no need for any appreciable 'out of merit' operation of local plant.

Kariba Station Arrangement (*Section* 5.1.2).—Since the paper was written the station arrangement has been modified and the 18 kV reactor circuit-breakers are used to control the station transformers, as stated in our reply to Mr. Newman.*

330 kV Cables (*Section* 5.1.5).—No special arrangements were necessary to deal with the high static oil pressure except that an automatic valve is incorporated in each sealing end to close the oil channels if the flow exceeds the normal velocity, for example following severe damage to a sealing end.

Substation Arrangement (*Section* 5.2.1).—The intermediate substations are arranged on a common plan which permits them to be developed from a simple initial installation up to a major double-busbar switching centre in easy stages and without a major interruption of supply. This development would be more difficult if the mesh arrangement were adopted.

Switchgear (*Section* 5.2.2).—In specifying a total break time of four cycles it was appreciated that a number of 330 kV circuit-breakers are available which have a total break time of three cycles and even slightly less. On the other hand, there are also circuit-breakers which do not quite achieve four cycles but which have other advantages making them worthy of consideration. Further shortening of total time below three cycles would enter a region of diminishing net returns and would increase the ratio of asymmetrical to symmetrical breaking-current rating. Nevertheless the achievement of higher speeds may be worth while if accompanied by reliability and low cost.

The difference in opening time between phases in circuit-breakers having three mechanisms was found on test to be about 0·005 sec, and this is quite acceptable in the present application. In a reply of this kind it is not possible to describe all the many factors which need to be taken into account in arriving at a maximum permissible time discrepancy.

Transformers and Reactive Plant (*Section* 5.2.3).—There is not a great deal of difference technically or economically between 220 kV, 66 kV or mixed-voltage transformers for Kitwe, and the choice was made to suit the requirements of the R.C.B.P.C.

It will not be possible to substitute the spare single-phase generator-transformer unit without an outage of the 3-phase bank.

We have had experience of capacitor voltage transformers in a number of systems, and although difficulties have sometimes been encountered, we are satisfied that they can now be considered reliable. Condenser bushings are not being used to provide voltages for relaying and metering.

The 220 kV boosters are separate units comprising a tapping unit and a series unit in the same tank, the primary of the tapping unit being supplied from the 11 kV tertiary winding of the main 330/220 kV transformer. The tap-changers are of the resistor type.

Transmission Lines (*Section* 5.3).—The extended stress/strain tests on the proposed conductors gave sufficiently conclusive results to reassure us about the allowances being made, but we agree that it is unwise to be too dogmatic about the degree of settlement of s.c.a. conductors.

Although there are technical objections to certain types of tubular tower design, there was no offer for this system which compared favourably on economic grounds with the design using angle sections.

No specific radio-noise-level figure can be quoted for the Kariba system, but the design employs margins over the corona onset voltage which have been found to give acceptable radio-interference performance on a number of other systems now in service. The estimated corona loss is 1 kW per mile.

All conductors are transposed in turn and one complete rotation is made in each major line section.

In general, no compensation payments for right of way have been necessary as most of the country traversed is uninhabited Crown land. Compensation has been paid over certain quite small sections. Similar remarks apply to the land covered by the lake so far as actual compensation is concerned, but a series of habitations and a population of about 40 000 people have been moved to new village sites with transport provided by the Government authorities and with compensation paid to each family for disturbance. The creation of such a huge lake would certainly be difficult anywhere except in relatively undeveloped territory.

Counterpoises (*Section* 5.3.5).—In spite of the high soil resistivity the measurements taken on the lines constructed so far indicate that the continuous counterpoises can be relied upon to reduce the effective footing resistance sufficiently if the measured individual values exceed the 20-ohm limit specified. It is, of course, not possible to say in advance of service experience that this guarantees a particular maximum rate of back flashover. The total cost of counterpoise is about £250 per mile.

Protection (*Section* 5.4.1).—The acceleration signal in the protection is achieved by carrier suppression, but this is coded to provide a more reliable signal than the single momentary suppression method tried in earlier schemes.

Communications (*Section* 5.4.3).—The main communication system is designed in conjunction with the power-line carrier, which was considered necessary for the protective and control scheme as this was more economical than the use of a separate radio system for communication. Radio could have been employed for the whole protection and communication scheme using v.h.f. equipment, but this was found to be somewhat more costly than the carrier arrangement.

With regard to the Post-Office-type cables parallel to the transmission lines, tests are being made to determine the induced voltages in sections where appreciable parallelism will occur.

* *Proceedings I.E.E.*, 1958, 105 A, p. 603.

DISCUSSION ON

'THE DESIGN AND PERFORMANCE OF THE GAS-FILLED CABLE SYSTEM'*

Before the Western Centre *at* Bristol *9th February, the* South Midland Supply and Utilization Group *at* Birmingham *9th March, and the* North Staffordshire Sub-Centre *at* Stoke-on-Trent *30th October*, 1959.

Mr. A. G. Milne (*at Bristol*): At the beginning of the paper a claim is made that there is only a small degree of complexity with gas-filled cables as compared with the solid-type cables. This will be no consolation to the operation engineer, because any additional complexity, however small, is unlikely to commend itself to him.

The efficiency of the anti-corrosion outer serving causes misgivings. It is essential for a serving to be completely effective at all times on gas-filled cables, and more especially on the aluminium-sheathed variety. I suppose that a p.v.c. extruded covering could be an alternative to vulcanized-rubber serving, but I am not quite sure whether the carbon tape can be incorporated in the p.v.c. covering, which would be a disadvantage since it would then be impossible to test the efficiency of the anti-corrosion sheath. The economic case at the present time favours the 33 kV gas-filled cable. The first cost is cheaper, and although the losses are higher than in the solid-cable case, the overall capitalized costs are lower for periods of, say, 40 years with the load cycle and load factors obtaining in this part of the country. Similar calculations some years ago, however, showed that the overall cost of the solid cable was lower than the gas-filled cable at 33 kV. The reason for the difference was that metal prices and the shapes of load curve and load factors were not quite the same in both cases. These exercises proved that the capitalization of losses is only marginal and can be varied to show a gain or loss by a small difference in the elements of the formula. For this reason, too much importance should not be attached to the overall effect of losses in economic assessments.

We have had gas-filled cables in our area for some time now, and apart from leakage troubles in the joints at the time of installation, no troubles have been experienced.

Before the advent of the 33 kV gas-filled cable when compound migration was a problem on undulating routes, the pre-impregnated solid cable had an advantage over the mass-impregnated cable in that no special barrier or stop-joints were necessary and there was no danger of burst lead sheaths. Could the authors say whether the 33 kV pre-impregnated gas-filled cable holds the same advantage over the mass-impregnated gas-filled cable?

Mr. G. S. Buckingham (*at Birmingham*): We in the supply industry attach importance to the rubber sandwich finish—the 10 kV serving which is applied over the reinforcing tapes—for the success of the gas-filled cable depends on their integrity. We have recently had installed in the Stoke-on-Trent area a 3-core cable with this type of finish, and are looking forward to seeing the results of the tests on this outer sheath, which will indicate whether any moisture has penetrated into the reinforcement maintaining the 200 lb/in^2 pressure within the sheath.

We are apprehensive about reinforcing tapes, either longitudinal or circumferential, and have had some trouble with them. We are therefore very interested in the suggestion in the paper that some other types of tape can be used for reinforcement, such as glass fibre or plastic, which might enable us to use less expensive finishes overall. Will the authors give more details of the alternative materials now being used which might remove some of the difficulties we have had?

The paper refers to the possibility of using plastic tapes interleaved with paper tapes for insulation. Such an arrangement would be valuable in very-high-voltage cables, but the cables we use do not normally exceed 33 kV and we already have a very thin dielectric, so that I expect the advantage of interleaved plastic tapes would not be very great.

People sometimes ask why we seek cheap cables, which, they say, have a life of only 20–25 years. We believe that we are installing cables for a life of 100 years. We hope we are doing something for posterity, and the cheaper we make our distribution network now, the cheaper is electricity going to be for the next generation.

Mr. R. Rockliffe (*at Birmingham*): There are approximately 26 000 yd of gas-filled cable in the Birmingham area, some 15 000 yd of which has been in service for 10 years. The operational experience of this cable has been entirely satisfactory and no faults have occurred.

Section 4.5 refers to the effect of moisture on the cable dielectric and states that 'Experimental results confirm that gas-filled cable manufactured with moisture contents within the range given in Section 4.5.2 would have an adequate margin of safety with respect to all important electrical characteristics'. The authors make no reference to the moisture content of nitrogen, and it may well be that commercial nitrogen is wet compared with the moisture contents referred to in the paper. Do the authors consider some type of drying agent installed in the gas-feed circuit would be an advantage, or is the amount of moisture in the nitrogen negligible for all practicable purposes?

It is stated that insulation of the fully insulated straight joint was obtained by using a p.v.c. sleeve which was welded on site. P.V.C. welding is a new technique, and I should like the authors' opinion on its use on site where conditions are far from ideal. Since there are now many excellent and reliable adhesive compounds, I should like the authors' opinion on the use of these as an alternative to p.v.c. welding.

Mr. H. M. Fricke (*at Birmingham*): I should like more details of the thermal characteristics of the solid type of cable when compared with the gas-filled type.

Super-voltage cables of large section could be assumed to carry several million pounds' worth of electric power during the course of their life. The copper section is fixed, between close limits, by thermal requirements. The reduction in insulation thickness gives an economy on insulation costs and a small saving in lead-sheath diameter and in the servings overall. These economies are obtained as a result of high stress on the insulation, and they are so small, relative to the annual value of the power transmitted, that a case could be made out for a return to thicker and less highly stressed insulation.

Mr. I. G. Edwards (*at Birmingham*): The use of graded and pre-impregnated papers for dielectric purposes has enabled a better stress distribution to be obtained in this form of cable compared with the mass-impregnated cable. I think that the appropriate stress at 33 kV for this type of cable is 75 kV/cm against 85 kV/cm for the mass-impregnated cable. In the latter

* Thornton, E. P. G., and Booth, D. H.: Paper No. 2574 S, October, 1958 (see 106 A, p. 207).

we had troubles due to frothing if rapid degasification took place, but this is, of course, avoided in the pre-impregnated cable; these are but two improvements in the new design.

All modern types of gas-filled cable have good service records so far as electrical faults are concerned. Generally the incidence of faults on underground cables due to mechanical damage is increasing, certainly in city distribution networks, and one of the disadvantages of the gas-filled system is, of course, the additional time required to re-gas the cable over and above that required for the normal repair of the joint. Nowadays the provision of standby circuits is not based on the full capacity of the plant to which they act as standby; for example, three circuits might have to act as standby for eight or ten other loaded circuits, so that anything which can be done to reduce still further the time taken for regasification after mechanical damage is worth investigating.

Coming next to accessories, the usual allowable longitudinal stress in straight joints on cables of the mass-impregnated type was stated in a previous paper to be 1·5 kV/cm, while in straight joints on pre-impregnated cable it is 3 kV/cm. Is there any particular reason for this? Is the paper electrically stronger, or is it that the fully screened joint design illustrated has enabled a better stress distribution to be obtained?

Mr. J. S. Woodhouse (*at Birmingham*): Can the authors say that all electrical faults are accompanied by a fall of nitrogen pressure or an increase of the rate of feed of gas to the cable?

With a system comprising an overhead line and a section of underground cable, it is generally supposed that the 33 kV overhead line will cause transient trips. Could not the controlling switch be immediately closed with a very considerable assurance that no fault exists on the cable, provided that gas pressure is being maintained?

Is the use of compression jointing and sheath seaming being undertaken seriously now that the use of single-core cables and cross-bonding has become a practical application so far as 33-kV cables are concerned? This method could lead to considerable economies in jointing, and the elimination of soldered joints should lead to a further considerable uprating of the conductor temperature.

Mr. P. Finch (*at Stoke-on-Trent*): A very large proportion of the ground within the city of Stoke-on-Trent is formed by continual deposits over a century or more of waste from the pottery industry; this waste, consisting of a mixture of shards, saggers and ash, is known locally as 'shraff'. Difficulty is experienced in laying cables in such ground, since the pieces of broken crockery have sharp edges which damage the protective covering of the cables, while the deposits of ash cause rapid corrosion of the steel wire armouring. Experience over many years has proved that the most successful method of installing cables in such condition is to lay them on bridges in earthenware troughs, which are then filled with pitch and covered with tiles.

It is extremely doubtful whether the vulcanized-rubber-sandwich protective covering of a gas-filled cable laid direct in this type of ground would provide satisfactory protection for the cable. The life of a gas-filled cable is primarily the life of its steel reinforcing tapes, and this in turn depends upon the life of the protective covering. Have any tests been performed to determine the life of the vulcanized rubber sheath? It would also be interesting to know the additional cost of providing reinforcing tapes of 1% tin-bronze. Such tapes have lower electrical losses, permit a higher current rating of the cable and are less susceptible to corrosion. What progress is being made in the development and application of p.v.c. armouring for the protection of the rubber sheath?

When the gas-filled cable has been installed using the all-insulated system, periodic tests can be carried out to determine the condition of the rubber sheath. Since this rubber contains carbon particles, its insulation resistance will decrease within two or three years and it will therefore be difficult to determine whether the increase in test current results from a general increase in leakage current or from a small hole somewhere in the rubber.

What progress is being made in the development of a 132 kV 3-core cable?

Mr. E. J. Waddon (*at Stoke-on-Trent*): Why did the authors use an oversheath of vulcanized rubber in preference to an extruded thermoplastic material as a protection against corrosion?

The possible future use of aluminium-sheathed gas-filled cables has been mentioned: since the length of an aluminium cable sheath of the type manufactured by the authors' company is limited by the amount of metal contained in one billet, would not this mean that the cable would be supplied in much shorter lengths than at present, and there would be a considerable increase in the number of joints per mile run of cable?

Messrs. E. P. G. Thornton and **D. H. Booth** (*in reply*): *Mr. Milne.*—A p.v.c. extruded covering used as an anti-corrosion serving would not normally be protected by textile tapes as is the case with the present vulcanized-rubber serving. In a buried direct installation, therefore, the soil would act directly as the outer electrode and there would be no point in having the carbon tape which has proved to be so invaluable in the present finish. There is still a difficulty with factory testing, and this would be covered by spark testing during extrusion or by painting the outside of the p.v.c. with graphite. We agree that very great care is needed in deciding to what extent capitalization losses should affect an overall assessment between different cable systems. The difficulty is that comparatively small changes in the assumptions necessary for capitalization can make significant differences in the estimated annual cost of any system. The 33 kV pre-impregnated gas-filled cable is non-draining, and certainly does not require the use of barrier or stop joints, nor is there any danger of burst lead sheaths due to compound movement. The possibility of frothing of free compound during degasification is also avoided.

Mr. Buckingham.—Our work on the non-metallic reinforcement of gas-filled cables has shown that there are serious difficulties in maintaining the necessary bond strength between a flexible resin and glass fibres when under the moist or wet conditions which would appertain with cables laid in the ground.

Since the paper was written there has been a growth in the interest of aluminium-sheathed cables, mainly, we feel, because of the introduction of the all-insulated method of system operation and to the confidence that has been obtained by experience in the wiping on to aluminium sheaths. This development has, of course, had a secondary effect of removing the apprehension felt in some quarters about the use of reinforcing tapes. Mr. Buckingham is correct in thinking that the use of plastic tapes is not likely to have an economic advantage with 33 kV pressure cable.

Mr. Rockliffe.—If commercial (rather than the drier 'oxygen-free') nitrogen is used in charging gas-filled cable, we recommend that the cylinders should not be emptied to pressures below 500 lb/in^2, since serious moisture contamination can occur below this. For this reason we always recommend the drier grade of nitrogen for permanent installation in gas-charging cubicles, and under these conditions a drying unit in the gas-feed circuit is unnecessary. P.V.C. welding is a well-established technique and, in fact, is probably better proven than the adhesive compounds which are recommended for fabricating p.v.c. joint sleeves. We are well aware of the simplicity associated with the use of adhesives, but we consider that their efficacy after long

periods in wet soil has not yet been proved but are watching developments in this direction very closely. We have now welded several hundred joint sleeves on site and have experienced no difficulties once the technique has been mastered by the individual jointer.

Mr. Fricke.—The maximum operating temperatures of solid and gas-filled cables are 65 and 85° C respectively, and their dielectric thermal resistivities are identical at 550 thermal ohm-cm.

Mr. Edwards.—Any gas-pressure system has the advantage that, if it is necessary to insert a short length of cable when mechanical damage has occurred, it is a simple matter for both repair joints to be manufactured simultaneously. Regarding regassing, it is our experience that a system, once it has been initially charged, can be regassed very quickly, particularly if use is made of the intermediate gas-charging points. The screened-joint design does give a better control of longitudinal stress than the semi-screened design, and this is probably the main reason for the increase of stress over that previously quoted for joints in cable of the mass-impregnated design. We feel also that the 1·5 kV/cm quoted was a conservative figure and should be considered as a minimum value.

Mr. Woodhouse.—To the best of our knowledge all electrical faults have been accompanied by a fall of the gas-cylinder pressure, indicating the feed of gas into the system. With very long systems it is possible for there to be a short delay before this fall is registered at the control cubicle. We have not carried out any serious work on compression jointing or sheath seaming. Loads at 33 kV have not yet justified the use of single-core cables and cross-bonding, but the technique is now well established for high voltages.

Mr. Finch.—During the development of the CR_2CH_2 finish many tests were carried out to determine the long-term ageing characteristics of the rubber layer. There are, however, so many variables which may affect the life of the corrosion protection that our confidence in the use of the rubber layer has been based more on the proven performance under onerous conditions of heavy-duty t.r.s. cable than on the good results of laboratory tests. It is for this reason that the rubber compound of our CR_2CH_2 finish is based on a tough rubber rather than a softer dielectric quality.

The additional cost of applying 1% tin-bronze in place of steel for reinforcing tapes would be of the order of 5–6%. On all projects, however, both materials are considered and the final choice is based on obtaining the best balance between current rating and cost.

Our interest in semi-rigid p.v.c. armour wires has been confined to lower-voltage cables, to provide high abrasion resistance, and we have not made a serious study of their potential as a mechanical protection for the rubber layer of the anti-corrosion finish of a pressure cable.

We agree that, since any rubber or thermoplastic sheath will absorb moisture, there will be a tendency for the insulation resistance of the sheath to decrease significantly with time; but the use of the correct grades of carbon black in no way increases the permeability.

In our experience, where mechanical damage to a serving has occurred, there has been no difficulty in establishing the presence of such a fault by comparing the leakage current of the serving on the suspect length with that on an adjacent length.

It is probable that a 132 kV 3-core gas-filled cable will be available in 1960.

Mr. Wadden.—When anti-corrosion coverings were used in the place of the second lead sheath our knowledge of rubber materials, particularly regarding their application, was far greater than our knowledge of the thermoplastics, and the decision to use rubber was therefore both obvious and correct at that time. Since that decision was made there have been important advances in the technology of extruded thermoplastic coverings, and it is therefore quite probable that they will become of much greater importance in the future.

We agree that the use of aluminium sheathing can limit the length of any individual cable section, and it is therefore always necessary to judge the relative merits of lead and aluminium sheathing for any project with this limitation in mind. In general, however, for the conventional type of 33 kV distribution system in a built-up area we have not found that this length limitation provides a serious problem.

DISCUSSION ON 'EXAMPLES OF GEOELECTRIC SURVEYS'*

NORTH-EASTERN MEASUREMENT AND ELECTRONICS GROUP, AT NEWCASTLE UPON TYNE, 16TH MARCH, 1959

Mr. G. H. Hickling: From the manner in which the symbol ρ_s for the apparent resistivity at a depth h is used in the paper, the impression is conveyed that one can obtain, from the surface measurements, a discrete measurement of the resistivity of a stratum at any specific depth. It is evident, however, from a consideration of the physical factors involved, that only the incremental change in the value of R can be influenced by the resistivity of a stratum of depth h as the spacing a approaches this value. A sudden change in earth resistivity with depth would not be expected to result in a corresponding jump in the ρ_s/a curve.

For the above reason it is difficult to believe that a sudden kink in the measured ρ_s/a curves, such as is shown in the curve B10 of Fig. 3, can be associated with a particular thin layer of rock of higher resistance. One intuitively feels, on the other hand, that the field measurement must inevitably be subject to local variations of the surface resistivity along the line of traverse at a particular station, and that such effects may well explain the kinks shown in Fig. 3. Is the explanation given for these in Section 2.5 not reading too much into the experimental data?

With reference to the Pen Park Hole observations, can the author explain the remarkable difference between the minimum ρ_s values in the curves for stations 5 and 6 (attributed to the boundary of the water in the hole), bearing in mind that these two stations are apparently only 20 ft apart, whilst the cavern is some 150 ft in depth, and that the current by which the presence of the water is detected must necessarily flow under the cavern?

The paper deals with three specific geological anomalies. It

* PALMER, L. S.: Paper No. 2791 M, December, 1958 (see 106 A, p. 231).

would have added much to confidence in the method if a few examples of observations on simpler geological formations, well substantiated by borehole data, could have been included.

Have the resistivities of all the common rocks now been evaluated, and is the value for each sufficiently constant to make reliable deductions? Has the effect of changes in the height of the water-table been determined by systematic checks against natural seasonal variations, or by studying the effect of varying pumping rates from boreholes? The local effect on the geoelectric observations of the cone of depression of the water immediately around a pumping station would seem to be of particular interest.

Has use been made of 3-dimensional laboratory models, representing specific geological formations, to confirm by practical tests the geoelectric indications which would be obtained? Such a technique, using clays of varying resistivity, ought to be the ideal method of checking field observations, as well as for testing the suitability of the technique in given circumstances.

Professor L. S. Palmer (*in reply*): Mr. Hickling's interesting comments clearly emphasize some of the difficulties, both theoretical and practical, which occur in geoelectric surveys.

The fact that the units of apparent resistivity are ohm-feet (or ohm-centimetres) makes this quantity very difficult to visualize physically. Furthermore, calculated values refer to particular localities, not to specific points. Variations in the ρ_s/a graphs arising from relatively sudden geological discontinuities below the surface at a depth h occur gradually, and a particular point of inflection on a graph does not, in general, appear at a value of a equal to h, at which there is a sharp discontinuity. By changing the electrode configuration on the surface, the critical value of a can be varied for a discontinuity at a fixed depth. This is discussed in Reference 19 of the paper.

In curve B10 of Fig. 3 the magnitude of the kink is dependent on the volume of the gravel seam. Consequently, a thin seam produces marked kinks at the same value of a on graphs covering a relatively large area. A much thicker seam of limited area may produce an insignificant effect on the graph.

One of the most serious practical difficulties in geoelectric surveying is the large effect of relatively small surface irregularities. But such irregularities were not present on the Holderness Plain and cannot therefore account for the regular series of kinks all about 60 ft below stations along the line BB′ and from 20 to 30 ft below stations on the line CC′ in Fig. 2.

With regard to the graphs for stations 5 and 6 at Pen Park Hole, I fully agree with Mr. Hickling that the results are remarkable. I would also add that they were quite unexpected. The lower portions of the graphs for stations 2 and 3 were like 5 and those for stations 7 and 9 were like 6. The water boundary in the cave was not sharp but graded off into wet mud. Hence the marked difference between graphs 5 and 6 is the more surprising. The curves are, however, based on depth readings at 20 ft intervals below 150 ft, and the curves are quite smooth and regular, as shown in Fig. 13. No other interpretation seems to be either possible or applicable.

With regard to the values of the apparent resistivities of the more common rocks, these have been evaluated by several authorities and were listed in 1943 in a publication entitled 'The Location of Underground Water by Geological and Geophysical Methods'. The pamphlet was issued by the G.H.Q. of the Mediterranean Expeditionary Force and was based on work carried out by the 42nd Geological Section, S.A.E.C. Values vary widely with moisture content, and extreme ranges for different rocks often overlap. This results in ambiguous interpretations unless guidance can be obtained from a knowledge of the geology of the particular locality.

Geoelectric measurements of the seasonal variations in the levels of water-tables have not yet been carried out as far as I am aware. Systematic geoelectric records in the neighbourhood of pumping stations would probably lead to valuable and certainly interesting results.

Finally, work on models was undertaken, but difficulties with the production of graphite-loaded pastes necessary to make the electrical dimensions of the materials conform to the geometrical scale of the model prevented any conclusive results from being obtained during the time available for this work.

DISCUSSION ON 'THE DELTIC LOCOMOTIVE'*

Before the NORTH-WESTERN UTILIZATION GROUP *at* MANCHESTER *13th January, and a* JOINT MEETING *of the* NORTH MIDLAND CENTRE *and the* SHEFFIELD SUB-CENTRE *at* WAKEFIELD *3rd March,* 1959.

Mr. F. Whyman (*at Manchester*): Too much emphasis is placed upon the general desirability of obtaining a high power/weight ratio when experience shows that for most applications, particularly freight and mixed traffic, the ratio obtained with a conventional locomotive meets requirements, substantial adhesion being necessary to start heavy trains on adverse grades. The main advantage of the high ratio is for passenger locomotives, where only modest adhesion and tractive effort are necessary—although involving high power to obtain high speeds—and for oversea narrow-gauge low-axle-load systems where a high ratio would be very useful. Bearing on this, the 1 200 h.p. locomotives for Ireland listed in Table 1 would still have to weigh 85 tons with all axles motored to provide adequate adhesion, however light an engine had been used.

The author suggests that 3 300 h.p. would appear to suit British Railways' requirements, because this figure is specified for their electric locomotives. However, the 3 300 h.p. of the Deltic is at the engine shaft, the rail horse-power being about 2 700 at peak efficiency, whereas that of the electric locomotive is the continuous power at the rail. The latter is also able to develop 6 000–7 000 h.p. at the rail for lengthy periods, this being very useful for rapid acceleration to high speeds.

In spite of the author's claims, I consider that the series arrangement of motors with equalizing connection (Fig. 3) will not nearly achieve the adhesion possible with parallel connection in an a.c. locomotive. It appears unfortunate that the Deltic should have this deficiency, and also the series connection of generators, where flashover on one may affect the other.

While the author does not feel that the two power units are necessary for security, I consider it a good insurance against failure in service. In the United States, where most freight trains are hauled by a 2-, 3-, or 4-unit locomotive, it is not unusual for one unit to be out of service, but timings will be substantially

* COCK, C. M.: Paper No. 2769 U, December, 1958 (see 106 A, p. 107).

cept. With single-unit locomotives there is a strong case for two engines.

The experience with the Deltic to date appears very encouraging, but to be competitive commercially with other forms of motive power, its reliability, maintenance and operating costs per trailing ton-mile must be proved acceptable. This is probably the biggest query with the Deltic. The author states that maintenance is on an 8-hour engine replacement basis, but since many apparently serious repair operations can be done *in situ* on a conventional engine in 2 or 3 hours, it seems drastic to face up to 8 hours and still have the work to do when the engine is removed. High availability and low maintenance costs would thus appear more doubtful with the Deltic than with a conventional engine.

During a recent tour of the United States I found a preference for the 2-stroke engine over the 4-stroke, purely because piston rings could be easily examined through the inlet ports. Since piston rings appear to be one of the main casualties in traction engines, seized pistons occur rarely on the 2-stroke engine but frequently on the 4-stroke unit. Is easy piston inspection possible with the Deltic engine?

Since so much of railway operation is done at part loads, could the author give more information on the part-load efficiency of the Deltic engine? Fig. 11 indicates an overall efficiency of $24\frac{1}{2}\%$ with a 600-ton train at 50 m.p.h., falling to $21\frac{1}{2}\%$ with a 300-ton train, and this fall would appear greater than with conventional engines.

Mr. G. R. Higgs (*at Manchester*): On the subject of lightweight engines, I am puzzled by the ton-for-ton principle given in Section 1. Most of the weight saving would be in the underframe and body (assuming that buffing stresses permitted any saving there), and then it is hard to see any more than about one-quarter of the claimed ton-per-ton ratio. Any further saving in the bogie frames and running gear is much smaller still.

Three reasons are given for selecting the opposed-piston design, and it is interesting to note that the loop-scavenge engine enjoys two of these features, namely the absence of valve gear and the efficiency of scavenging, for though it may seem strange, the loop-scavenge system has proved almost as effective as the uniflow. Presumably, as in other makes of opposed-piston engine, the powers delivered by the two pistons are not equal, giving the apparent anomaly of the same diameter, stroke, gas pressure and mean piston speed, but different power. The explanation lies, of course, in phasing, the gas pressure and piston speeds being phased differently—in electrical terms the power factor is not the same for the two pistons.

The author refers to the favourable effect of the automatic voltage-control system on wheel slip. Surely, if the voltage-control system had time to act during wheel-slip conditions, its effect would be unfavourable, since wheel slip causes current reduction and the automatic control would make the voltage rise, whereas a drop in voltage is what is required for stability.

Mr. D. A. Hawkins (*at Manchester*): Would a single 36-cylinder engine, had it been available and feasible, have shown any great saving of weight over the present arrangement?

Section 3.3.1. refers to high-pressure air-brake cylinders. What is the actual pressure and why was a higher pressure required?

The later fitting of shock absorbers between the equalizing beams and bogie frames is mentioned. The springing here is by coil, without inherent damping, so it appears surprising that shock absorbers were not fitted initially. Is the bogie damped laterally?

Section 10.2.3. mentions a considerable rise in engine-room temperature with the engine inspiring warm air. The resultant through draught should prevent this. The trouble with the original engine air-intake ducts suggests that the engine is not so vibrationless as Section 4.2 implies. It is difficult to imagine a centrifugal blower producing air pulsations of sufficient magnitude.

I understand that the engine cooling radiators are of light alloy. Has there been any trouble with fracturing of these, and are they resiliently mounted?

It is interesting to see that the Post-Office-type relays gave trouble in the wheel-slip protection system (Section 10.4.1). Relays of this type were used for a vital function a few years ago in locomotives which certainly did not have good vibration characteristics and have not given any trouble, despite initial misgivings.

Mr. F. G. Tyack (*at Wakefield*): The power of the Deltic locomotive is given as 3 300 h.p., while in Section 11 it is stated that 2 200 h.p. was achieved at the drawbar. The latter seems a more realistic figure for comparisons, and on that basis the Deltic appears very similar in performance and weight to the Sheffield–Manchester C_0–C_0 electric locomotives. It is indeed a fine achievement to have included the Diesel engines and fuel tanks without significantly exceeding the weight of that electric locomotive. It is also very good to know that the weight/power ratio is the best achieved anywhere in the world. No doubt the Deltic engine is primarily the reason for the startling weight saving.

In view of the difficulty of having to operate at half-voltage only, if running one engine only, it might have been more appropriate to have the generators in parallel rather than in series. No doubt there was a sound reason for connection in series, and it would be interesting to know the reason.

Having recently observed a case of bad wheel-slip on the rear bogie of a Waterloo–Portsmouth multiple-unit train, I can visualize the over-sensitive wheel-slip devices described in Section 10.4.1 being a real nuisance. The particular bogie was starting on a portion of track badly fouled by standing steam locomotives. By the time traction was achieved there was a cloud of smoke surrounding the bogie.

Mr. H. G. McClean (*United States: communicated*): Normally the major American railways operating freight trains on the 2 200 miles between Chicago and the Pacific Coast have taken six days. In recent months intense competition between some of these has cut the running times successively, until it is now 3–4 days. This is an outstanding example of the general tendency towards faster schedules. It is applied to freight trains only. It is tending to involve the use of different units of motive power, characterized by higher horse-power concentration in single-locomotive units like the Deltic, but the power/weight ratio has remained substantially unchanged and is still as typified by the second example cited in Table 1 of the paper. American operating experience suggests that, on freight service, wheel slip limits the effective horse-power which can be utilized to 400–500 h.p. on an axle load of 60 000 lb.

Simultaneously with this railway demand, the principal American builder developed the application of exhaust turbo-charging to his standard 2-stroke Diesel engine, and thus made available a substantial increase in horse-power from the same Diesel-engine frame size. A new locomotive, with a general-purpose type of body, has a rating of 2 400 h.p. with six driven axles of 60 000 lb each. Such locomotives are now on order in substantial quantities for the major western American railways. While this would seem to match the development of a high horse-power locomotive such as the Deltic, the essential difference is that the American development is for application to freight, and it therefore sustains the same power/weight ratios (for adhesion reasons) and continuous tractive effort-ratings approximating at least 18 % of the adhesive weight.

There is undoubtedly an incentive to produce locomotive

units for both passenger and freight service of greater size and horse-power, but I believe that the Deltic should most properly be considered as essentially a passenger locomotive.

Mr. S. A. Vincze (*New Zealand: communicated*): The illogical method of rating Diesel-electric locomotives by the brake horse-power of the Diesel engine, electric locomotives by the total brake horse-power of their traction motors and steam locomotives by their indicated horse-power causes much unnecessary confusion, even within the ranks of railwaymen and railway engineers. What matters, from the aspects of both train performance and performance calculations, is the tractive force at the wheel rim and the corresponding locomotive speed, in other words the rail horse-power. To enable true comparisons to be made between various types of motive power, all locomotives should be assigned

(*a*) The continuous rail horse-power and the corresponding speed.

(*b*) The maximum tractive force, the permissible time duration of that force and the corresponding speed.

(*c*) The maximum permissible speed and the corresponding tractive force.

(*d*) The total locomotive weight.

(*e*) The adhesive weight.

(*f*) The locomotive running resistance at all speeds, or at least at the speeds corresponding to the continuous tractive force and the maximum tractive force.

Considering the Deltic locomotive in the light of the above, it will be seen that it is a 2 700 h.p. (rail) locomotive at 43·5 m.p.h., having a weight/power ratio of 88 lb/h.p.(rail) and a power/weight ratio of 25·5 h.p.(rail)/ton—a remarkable achievement for a Diesel-electric locomotive by any standards.

A Diesel engine produces some 750 kcal/h.p.-hour of waste heat at full load, and some 900 kcal/h.p.-hour at half load. Is there any reason why this heat, or part of it, should not be used for train heating, rather than a separate oil-fired steam boiler on the locomotive? If the steam boiler cannot be omitted, because of the inheritance of obsolete steam-train heating equipment, it should be more economical to use a separate boiler wagon which could be omitted when not required (e.g. with freight trains and passenger trains in the summer time); at present the extra weight of the boiler must be carried all the time.

I should be glad to learn

(*a*) The purchase prices of the prototype locomotive and of the production locomotives if ordered in batches of 10, 25 or 50 respectively.

(*b*) The total running cost of the prototype locomotive per gross ton-mile, referred to the total train weight (including weight of the locomotive), and its composition after 200 000 and 1000 000 miles of running.

Mr. C. M. Cock (*in reply*): *Mr. Whyman.*—The relative values of adhesive weight are already postulated in the Introduction to the paper. The series circuit has proved to be very satisfactory in service and the wheel-slip correction scheme most effective. The series connection of the generators is an inherently stable arrangement, even with unequal engine speeds, and permits dissimilar engine powers to be fed into a common motor network. Flashovers have not been a problem.

It is possible to see the piston rings by removing the exhaust manifolds.

The wide spread of efficiency indicated in Fig. 11 arises because the fuel consumption is plotted in pounds per locomotive drawbar horse-power-hour rather than the more conventional pounds per engine brake-horse-power-hour. The approximate specific fuel consumption of the engine is 0·377 lb/b.h.p.-hour (engine) at full load, 0·375 at two-thirds load and 0·377 at half load.

Mr. Higgs.—The ton-for-ton principle is a good general approximation proved by long experience. It cannot be applied over too wide a range, but for moderate changes in equipment weight it is reasonably correct.

The automatic wheel-slip correction scheme does not boost the generator voltage but effectively reduces both voltage and power until wheel-slip ceases, when the pre-slip conditions are smoothly re-established.

Mr. Hawkins.—There is no 36-cylinder engine available.

Unless a more compact arrangement than the Deltic can be visualized, one could not expect a reduction in weight.

A maximum pressure of 75 lb/in^2 is available for the air-brake cylinder.

Running without primary dampers was deliberate: this is a development locomotive and experience was required both with and without dampers. No lateral damping of the bogies is fitted or required.

The engine vibration is low for an engine of this type, and pulsations were responsible for failure in the air-intake ducting.

The radiators have not suffered fracture and are not resiliently mounted.

Mr. Tyack.—A wider range of traction-motor field control is used when operating on one engine only, which gives enhanced high-speed performance in spite of the limits on generator voltage. In any case, single-engine operation is used mainly for freight haulage, where very high speeds are not required. To operate the two generators in parallel would introduce difficult stability problems.

Mr. McClean.—For American methods of railway operation wheel slip is often the effective limit, and, of course, tractive effort rather than horse-power is the governing factor for a given axle load. Freight-train operation is very different in the United States from that in Britain. For British conditions the Deltic can work the usual run of freight trains on one engine.

Mr. Vincze.—Rapid initial warming of a British Railways 16-coach train requires approximately 20 000 B.Th.U./min, and this is not available with the Diesel engine idling. At full load and engine speed a surplus of heat is available, but 10 000 B.Th.U. are necessary to maintain the coach temperature. The question was thoroughly investigated in 1947, and it was finally decided not to obtain train heating from the engine exhaust, because of complication and cost. On the Continent, oil-fired boilers mounted on separate wagons are widely used for train heating, and this arrangement simplifies the locomotives considerably.

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